DYNAMICAL MODELLING OF PRESENT AND FUTURE CLIMATE SYSTEMS

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"Dynamical modelling of present and future climate system variability at inter-annual and inter-decadal time scales"

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The Steering Committee responsible for this project, consisted of the following persons:

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EXECUTIVE SUMMARY

The project on the dynamical modelling of the climate system builds on earlier work to establish the base capacity to undertake climate simulations. This initiative is in recognition of the maturing of the climate model as a core tool for climate investigation, and for facilitating research on issues that have before proved largely intractable. However, the use of climate models requires great care in order to avoid blind application where the results may be fundamentally flawed. Appropriate implementation of climate models thus requires careful development in order to:

- Understand the inherent strengths and weaknesses of a particular model
- Assess the appropriate model configuration and refine the tool for the domain in question
- Evaluate the model output – assess bias and error and space-time dependent skill

This report outlines key developments addressing these issues. The project has significantly advanced the capacity to apply climate models in a robust manner, and at the same time addresses key questions of concern for the water and other sectors about the regional climate system of southern Africa. The diverse activities of the project are in themselves significant research projects, linked by the common use of the climate model. In the process a vibrant interactive research team has been developed, spanning institutions and involving many more students and scientists than only those who have authored this report.

Within the scope of developing model-based research on the southern Africa climate system, the original project objectives were:

- To continue the capacity building and development of dynamical modelling
- To identify and interpret dynamic process controls
- To develop scenarios of future climate variability
- To interpret the future dynamics of the processes controlling climate variability
- To investigate the dynamics of extreme events through case study modelling.

These objectives have been well met. The capacity developed in terms of infra-structure and scientific personnel has been substantially advanced, and as a direct consequence there are active research lines being followed by post-graduate students and established researchers that now utilize climate models as the principal tool.

The research questions addressed with models have focused on investigating those aspects of the climate system for which there remains poor understanding. Central among these is the climate sensitivity to feedback mechanisms and the dynamic responses to external forcing – especially land-surface feedbacks to the atmosphere. The modelling studies have shown that the feedbacks are important, and the sensitivity of the climate system to these attributes is commensurate with the magnitude of inter-annual variability and projected climate change.

Furthermore, the results indicate the feedbacks may potentially exacerbate any climate change signal. The suggestion arising from these results is that the land-surface may play a notably more important role than perhaps has been previously thought in governing intra-seasonal variability, extreme events, and possibly the strength of the regional climate response to global climate change.

Complementing the study on climate system feedbacks has been development of the core modelling tools: an activity that tailors the characteristics of the model to optimize performance over the southern Africa domain. As a consequence of this work the modelling tools are now well understood in terms of their skill and error, while the development of the models is an ongoing and necessary activity. Building on this, the models have been stretched to understand the limits of their performance, and in one application successfully simulated local scale weather systems down to 500m resolution, and in doing so provided valuable insight on extreme events in the Western Cape.

Further to these activities has been the development of a number of new methods of analysis tailored to the needs of the model-based research. These provide valuable and necessary understanding of the models capabilities, especially in the application to climate change questions. In this regard the work has supported a number of climate change activities, and provides core results underpinning research within other complementary projects.

This work has also greatly strengthened the interdisciplinary ties between the core modelling researchers and scientists in other disciplines; notably with scientists at the National Botanical Institute and internationally in the USA and the UK.

Perhaps the most important recommendation that can be made at this stage is that momentum must be maintained! An excellent research team has been developed through the support of this project; a team that has all the requisite skills to make significant advances in our understanding of the regional climate system. Such capacity is a pre-requisite to continue with the important research about the climate system, and which is of notable importance to a broad range of society. Specifically, the following issues are deserving of special attention:

- Investigation of the vegetation and soil moisture feedback mechanisms
- Continued development of the modelling tools
- Coupling of the climate models with other components of the physical system (e.g. hydrological models)
- Development of appropriate means for the dissemination of products to ends users.

This WRC project has contributed to a notable development in research capacity within South Africa. This capacity is well positioned to develop further with direct benefit to the pragmatic needs of many sectors, including that of water resources. As noted by the recent report “Poverty and Climate Change” (African Development Bank et al., 2003), prepared by 10 development and environmental agencies: “climate change poses a serious risk to poverty reduction and threatens to undo decades of development efforts.” This is an issue that is possibly the single largest natural long-term threat to development in Africa, and an issue that can only be addressed through climate modelling.

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1. Introduction

This project on dynamical modelling of the climate system builds on earlier work establishing the base capacity to undertake climate simulations. This requires an infrastructural capacity (computational), theoretical knowledge, and importantly experiential knowledge. Given appropriate computational resources and IT skills it is possible to rapidly implement and run a climate simulation; to do so and obtain results of value is a significantly greater challenge. The application of climate models, far from being the panacea for climate research, is fraught with potential difficulties that can lead to results, which, on the face of it seem correct, yet may readily be seriously flawed.

Appropriate implementation of climate models thus requires careful development in order to:

- Understand the inherent strengths and weaknesses of a particular model
- Assess the appropriate model configuration and refine the tool for the domain in question, and
- Evaluate the model output – assess bias and error and space-time dependent skill

This is not to say that models are flawed to the point of no value. In contrast, models offer a sophisticated, and perhaps only, means to address critical issues where we have limited understanding of the climate system – issues which are foundational to developing management, adaptation, and policy response to a climate that is in transition; where the idea of a climate normal, at least on the generational time frame, is perhaps no longer valid. However, it is the sophistication of the models that necessitates care to arrive at results that are of value.

This project has as an overarching intention the development of within-country capacity to undertake further work on a broad range of climate-society issues. In developing this capacity the project has undertaken a range of activities that span a number of topics of core relevance to the societal and ecosystem vulnerabilities of southern Africa; activities linked by the common use of the climate model as the principal tool. Each activity is, in itself, a full research project that has led to papers and theses already published or in preparation, and in addition fostered a wide range of complementary projects while stimulating new lines of research and proposals for additional funding. In the process a vibrant interactive team has been developed, spanning institutions and involving many more students and scientists than only those who have authored this report.

Within the scope of developing model-based research on the southern Africa climate system, this project addresses a number of sub-objectives. Each of these is in itself a potential multi-year research topic. This project seeks to establish the foundations in each topic from which the work may be taken forward. The objectives, as presented in the project proposal, include:

a) To continue capacity building with regard to use of climate models and development of dynamical modelling. This follows earlier work undertaken with WRC and other funding resources that were largely focused on establishing the core computational resources, and building a model-literate team of researchers. A special focus was to improve the capacity and capabilities for nested modelling and for coupling of the components of the physical system. In this regard the models have been notably refined and adapted to the specifics of the southern Africa climate system.

b) To identify and interpret dynamic process controls. In this regard the use of modelling tools has allowed new research questions to be addressed, perhaps most importantly the questions surrounding the role of land-surface feedbacks and responses.

c) To develop scenarios of future climate variability. Past decades have highlighted the changing nature of the climate system inter-annual variability, and the consequent impact on society, and even here there is much that still remains to be addressed. The nature of the dynamics underlying past change and projecting the climate system response to anthropogenic forcing are both questions that can only be viably answered through the use of climate models.

d) To interpret the future dynamics of the processes controlling climate variability. This aspect covers a broad front of topics, and this project has sought to address some of the key foundations that are pre-cursors to further analyses.

e) To investigate the dynamics of extreme events through case study modelling. This area of the work lags the development in other areas as it involves aspects of modelling that have not previously been addressed by the research team. In particular the project has approached this topic through high resolution modelling and has sought to understand the characteristics of the models and their limitation when employed in this mode.

The report that follows presents an overview of the project activities. The technical details are kept to an overview level where possible; the full details of such aspects best presented in journal papers focused on the technical specifics relevant to the appropriate research community. Consequently the report focuses on some of the key topics addressed that are particularly pertinent to a wide range of interest groups.

2. Global Climate Models

Global Climate Models (GCMs) are the core tool for simulating the coupled climate system, including teleconnection and hemispheric scales linkages. GCMs simulate the global climate using physical representations of the atmospheric, land and ocean surface (note that here we refer only to the atmospheric component of GCMs which in a general sense may also include ocean models). A number of GCMs have been used in the project, some run on the local computational infrastructure, and some for which only the output data have been obtained from other modelling groups. The use of a range of GCMs is important as no one GCM may be considered the best; each having different strengths and weaknesses on different temporal and spatial scales. The following sections present an overview of the GCMs used in this project, their characteristics (spatial resolution, representation of atmospheric processes etc), outline some experimental changes applied, and reviews the representation of the observed climate. Evaluating their simulations of present climate encompasses a wide range of time scales: from intra-seasonal (less than 3 months) to inter-annual.

In all the experiments presented below the GCM is forced by either observed or perturbed Sea Surface Temperatures (SSTs) and it is this boundary forcing that the GCMs climate responds to. However, before a GCM can be utilized as an investigative tool it is necessary to quantify the response to this forcing in terms of their natural variability (how they represent the natural atmospheric variability), i.e. are they simulating a response that is significantly greater than the natural internal atmospheric variability? This is traditionally accomplished by running ensembles (multiple runs with perturbed initial conditions). The mean response is then evaluated relative to the spread of the ensemble members.

2.1 Model Principles

Three GCMs were closely investigated as part of this project, there being the three models run on local computational infrastructure. We describe here their salient features important when simulating climate. The three GCMs focused on here are the US Center for Oceans, Land and Atmosphere (COLA) model, HadAM3 (of the UK Meteorological Office) and the Australian CSIRO9 model. All three are state of the art GCMs but differ in their spatial resolution and physical representation of atmospheric processes.

COLA is a hydrostatic T30 spectral model with a nominal resolution of 3.75° in both latitude and longitude. The model is described by Kirtman et al. (1997) and has 18 unevenly spaced sigma levels in the vertical. Prognostic variables include surface pressure, divergence, vorticity, virtual temperature and specific humidity on all 18 levels with the Simple Biosphere model (SiB) (Sellers et al., 1986) representing the land surface.

HadAM3 is a hydrostatic grid-point model with a resolution of 2.5° latitudinally and 3.75° longitudinally. The vertical scheme uses hybrid eta coordinates on 19 levels with prognostic variables including zonal and meridional wind components, geopotential height, specific humidity, liquid water and potential temperature. Pope et al. (2000) give a comprehensive review of this model.

CSIRO is a hydrostatic spectral model (R21) and comprises of 9 vertical sigma levels, 64 zonal and 56 meridional (gaussian) grid points yielding a resolution of approximately 5.6° by 3.3°. A detailed description of the physical schemes used in this model is provided by McGregor et al. (1993).

2.2 Modifying HadAM3 for southern Africa

In order to investigate the flow of moisture and processes responsible for precipitation over southern Africa, a 15 year hindcast using observed SSTs was run using the atmospheric component of the UKMO unified model (HadAM3). This model is used for both climate simulations and weather forecasting and is considered a state of the art model for these studies. However, the model has notable biases in its December-February (DJF) climatology (Pope et al., 2000), especially over southern Africa. Of particular note in this region is the anomalously strong monsoon over east Africa, the overly strong convection in the western Indian Ocean and associated disruption to the easterly flow of moisture during summer. To evaluate possible improvements in skill it was decided to test the model using a Mixed Phase Precipitation scheme (MPP) which has been shown to be effective when used in operational short-range forecasts (Wilson and Ballard, 1999). Here we demonstrate the changes seen in the January-March (JFM) climatology of the model when MPP is included. We also look at the effect of MPP on anomaly predictions of key model parameters.

2.3 The HadAM mixed phase precipitation scheme

The mixed phase precipitation scheme as used in HadAM3 is a physically based scheme that models the transfer of moisture between the different forms of water: vapour, liquid, rain and ice. Wilson and Ballard (1999) describe the scheme and evaluate its performance for two mesoscale case studies over the UK. They find that the microphysical processes in a frontal cloud are well modelled and the prediction of supercooled stratocumulus is improved. Here we give a brief summary of the salient points of the scheme.

MPP uses equations based upon cloud physics and avoids as far as possible any parameterisations based upon a tunable number which cannot be measured. Some simplifications are necessary e.g. secondary ice nuclei production is excluded and ice particle and raindrop properties are parameterised in terms of their diameters. Ice is treated as a prognostic variable and the liquid and rain component diagnosed. The procedure of the scheme is to start at the top levels of the model and then work downwards calculating new quantities of vapour, liquid and ice at each level. Rain and snow are calculated from the change in the above quantities and are considered as a flux at the bottom of the model layer in question. The evaporation of rain and sublimation of ice are included in the scheme.

2.4 The effect of MPP on HadAM3 climatology

The main biases of HadAM3, with respect to ECMWF reanalyses (ERA), are documented by Pope et al., (2000). In this work we use the NCEP reanalyses for model validation and it is worth noting that Pope et al. (2000) remarked that NCEP-ERA differences may be as high as differences between climate model simulations. Pope et al., (2000) also show biases for the DJF season, whereas we will concentrate on the JFM season. It was found that October-December biases were similar but weaker than those in JFM. Another factor that may cause differences between our climatology and that of Pope et al. (2000) is our shorter (1982-1999) SST climatology. The climatologies below are from 15 year integrations of the model with (MPP) and without (STD) mixed phase precipitation. To eliminate any biases due to the choice of SST climatology all observed datasets were averaged for the same period (1982-1999). A summary of model biases and the effect of MPP on them is given below.

Figure 1a shows the 500 hPa geopotential height biases of the standard version of the model (STD) with respect to NCEP (STD-NCEP). Figure 1b demonstrates the change MPP makes to the standard model (MPP-STD). We hope to see changes reflected in Figure 1b to be in opposition to biases in Figure1a if MPP is to improve the climatology of the model and decrease its bias with respect to NCEP. Generally over the globe there is a low height bias in the model and MPP acts to increase the heights. Especially encouraging is that many of the positive/negative biases in the northern hemisphere are partly balanced by changes due to MPP, e.g. north America, north Atlantic and Siberia. The changes seen in sea level pressure (not shown) due to MPP reflect those seen in Figure 1, indicating that they are representative of changes in the lower troposphere. Noteworthy is that the low pressure bias over the Antarctic and the high pressure bias over the Arctic were improved with MPP. Of importance in an African context was a reduction in the low pressure bias over and to the east of Madagascar. However, it should also be noted that changes due to MPP are smaller in magnitude than existing biases with respect to NCEP.

Figure 2 shows the 200hPa velocity potential changes. This quantity has been corrected for the global mean and the gradients of the velocity potential indicate the strength of the divergent wind. Similarly, regions where the velocity potential is negative are associated with convective activity and ascending air masses whilst convergent, descending air is associated with a positive velocity potential. Pope et al. (2000) note that the strength of the divergent wind is too strong in HadAM3 and this means the Hadley and Walker circulations are too strong. With MPP the negative bias over the eastern and southern Pacific is increased. However, to a far greater degree the negative bias over the Indian Ocean, extending over Indonesia, Madagascar and southern Africa is reduced. This is seen as a definite improvement for modelling the climate over southern Africa. It indicates reduced convection to the north and east of Madagascar where a cyclonic bias has been observed to disrupt the flow of moisture over southern Africa from the east. Generally over the globe the changes with MPP counteract the biases seen in the standard version though are not large enough to fully compensate.

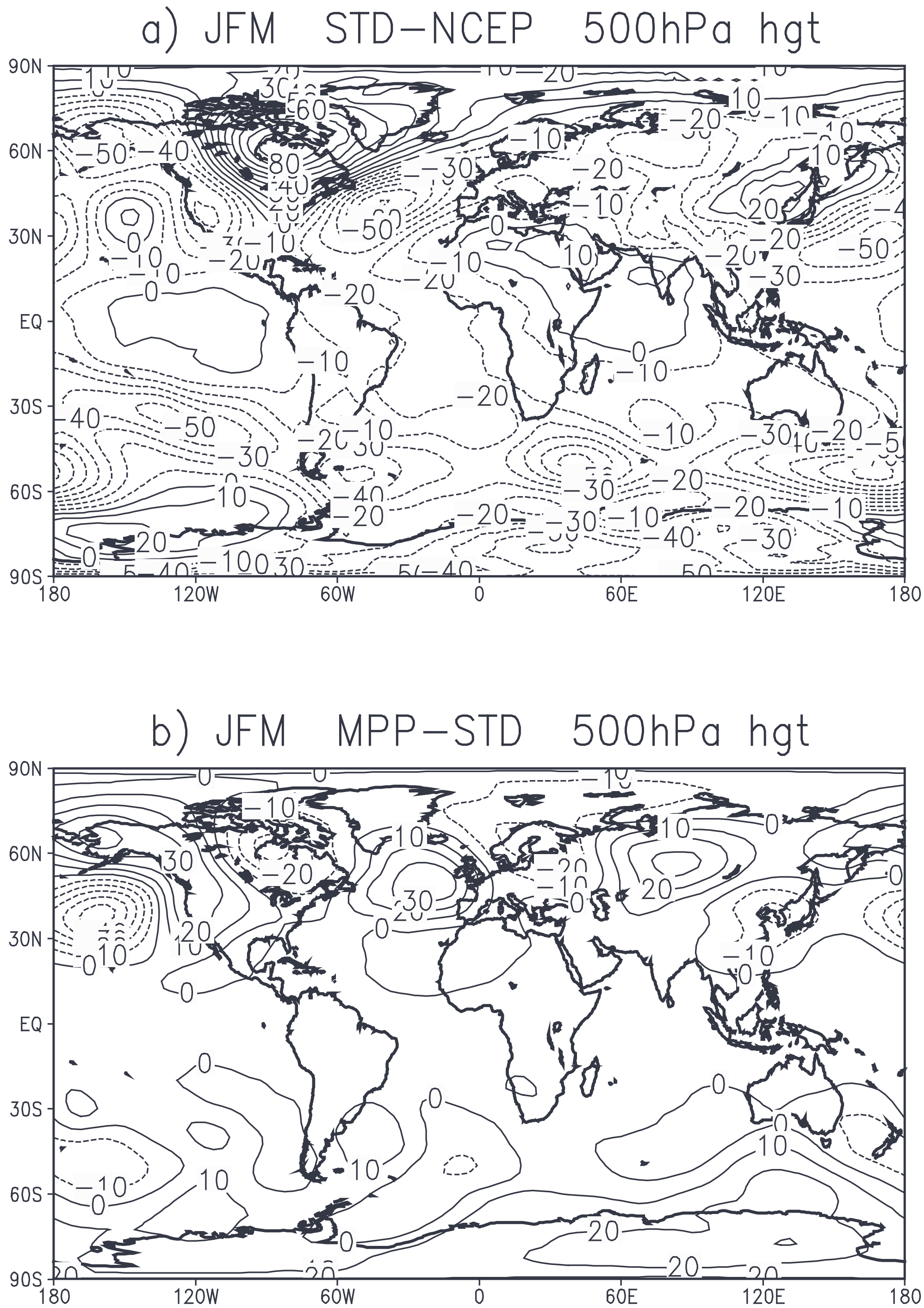


Figure 1: 500 hPa geopotential height biases. a) standard model – NCEP, b) mixed phase – standard.

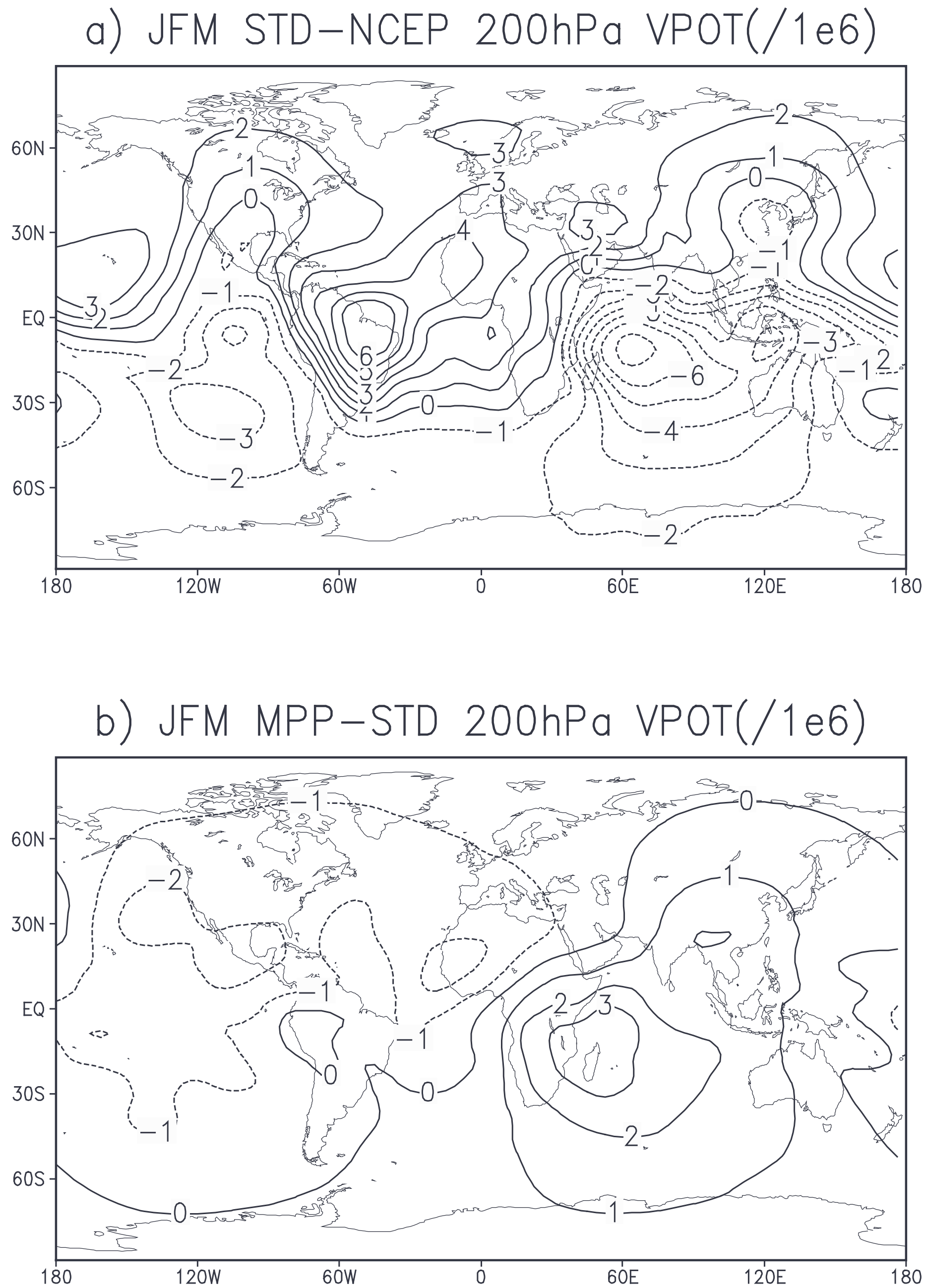


Figure 2: 200 hPa velocity potential biases. a) standard model – NCEP, b) mixed phase – standard.

The zonal mean temperature biases are given in Figure 3. It can be seen that MPP causes an increase in the temperature of the troposphere, with a slight cooling in the upper troposphere at high northern latitudes. These temperature changes are mostly in opposition to the biases with respect to NCEP. Interestingly the positive bias over the north pole with respect to NCEP is shown by Pope et al. (2000) to be a negative bias with respect to ERA. The positive temperature changes attributable to MPP are as high as 1.1K at 60N and 600 hPa, and average 0.5K in the tropical mid-troposphere. Below 400 hPa the changes made by MPP are approximately 60% of the magnitude of the original biases with respect to NCEP, but large negative biases remain in the upper troposphere.

Generally MPP reduces the specific humidity in the troposphere (not shown), except in the Inter-tropical Convergence Zone (ITCZ) where there is a slight increase. This leads to a larger negative bias in the mid latitudes but decreases the positive bias in the tropics. The changes in temperature and specific humidity result in a decrease of relative humidity throughout the troposphere. This in turn decreases the positive bias noted by Pope et al., (2000).

A brief description of other diagnostics and the effect of MPP on these is now given. Convective cloud (as deduced from the convective cloud liquid water path) is decreased over most of the globe, except in the region of the ITCZ where it is increased. Total cloud amount generally increases over the globe with a spatially extensive increase seen in the northern hemisphere. The outgoing longwave radiation (OLR) changes are the inverse of those seen in the total cloud amount as would be expected. Comparison with the Earth Radiation Budget Experiment (ERBE) (Harrison et al., 1990) shows that most of the positive bias in the northern hemisphere is improved. Most of the changes are small compared to existing biases. Convective rainfall is decreased everywhere, except in a small area of the central Pacific. Even where the convective cloud has been increased (ITCZ) there is a reduction in convective rainfall. Total rainfall is decreased over southern Africa and neighbouring western Indian Ocean, reducing the positive bias with respect to the CMAP precipitation (Xie and Arkin, 1997).

2.5 The effect of MPP on model dynamics and precipitation

We now look at the effect of MPP on the model response to SST anomalies, most notably those associated with ENSO in the central Pacific. These SSTs are the source of most variabilty in the atmosphere and have been linked to rainfall deficits over southern Africa, when SSTs are positive (El-Niño) and enhanced rainfall when SSTs are negative (La Niña). Figure 4 indicates the JFM mean 850 hPa eddy geopotential height difference between composite El-Niño and La Niña years. It can be seen that both MPP and STD versions of the model simulate the dynamical differences between El-Niño and La Niña well, especially in the central Pacific. However MPP can be seen to better represent the observed (NCEP) differences in other areas e.g. to the north-west of Australia. Importantly for modelling the climate over southern Africa it can be seen that the alternating positive/negative anomalies to the south of the continent are also better modelled in the MPP version of HadAM3. These anomalies relate to modes of variability in the westerlies to the south of the continent, which are known to be important factors in the formation of mesoscale precipitation patterns such as Tropical Temperate Troughs (TTTs). A similar plot of the difference in precipitation is shown in Figure 5.

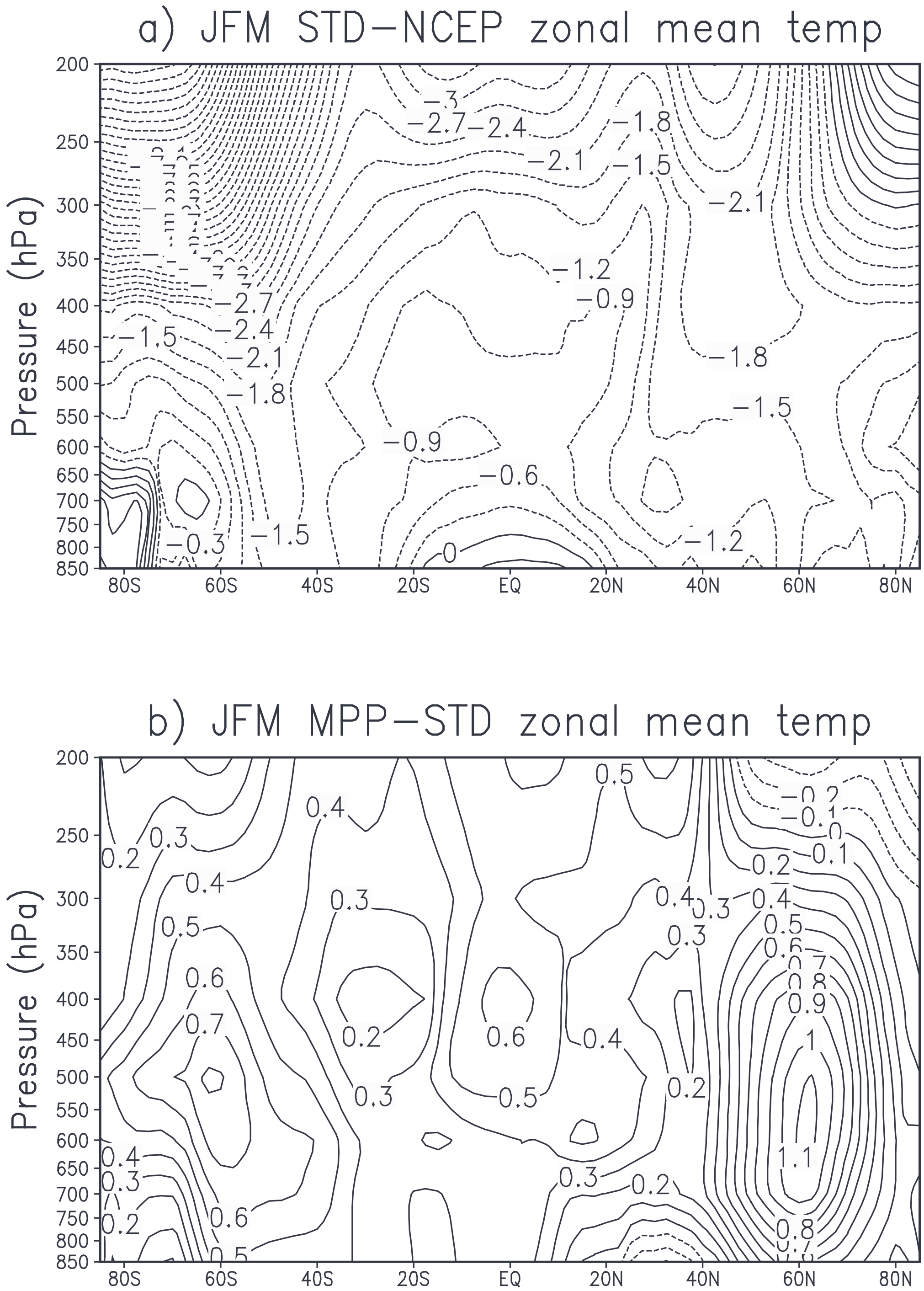


Figure 3: Zonal mean temperature biases. a) standard model – NCEP, b) mixed phase – standard.

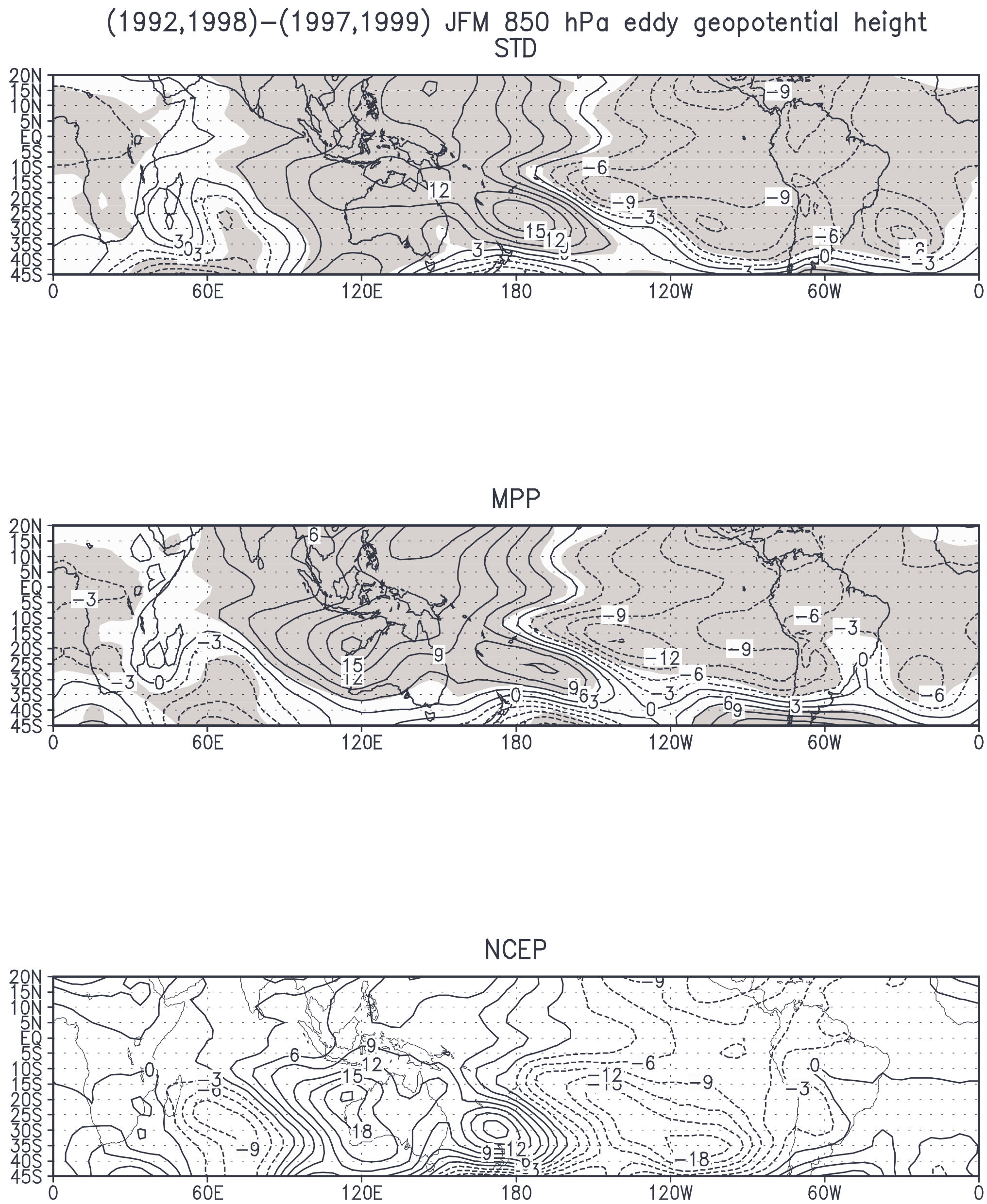


Figure 4: Difference in composite (El-Niño - La Niña) JFM 850 hPa eddy geopotential heights. Shading indicates differences significant at the 95% confidence interval.

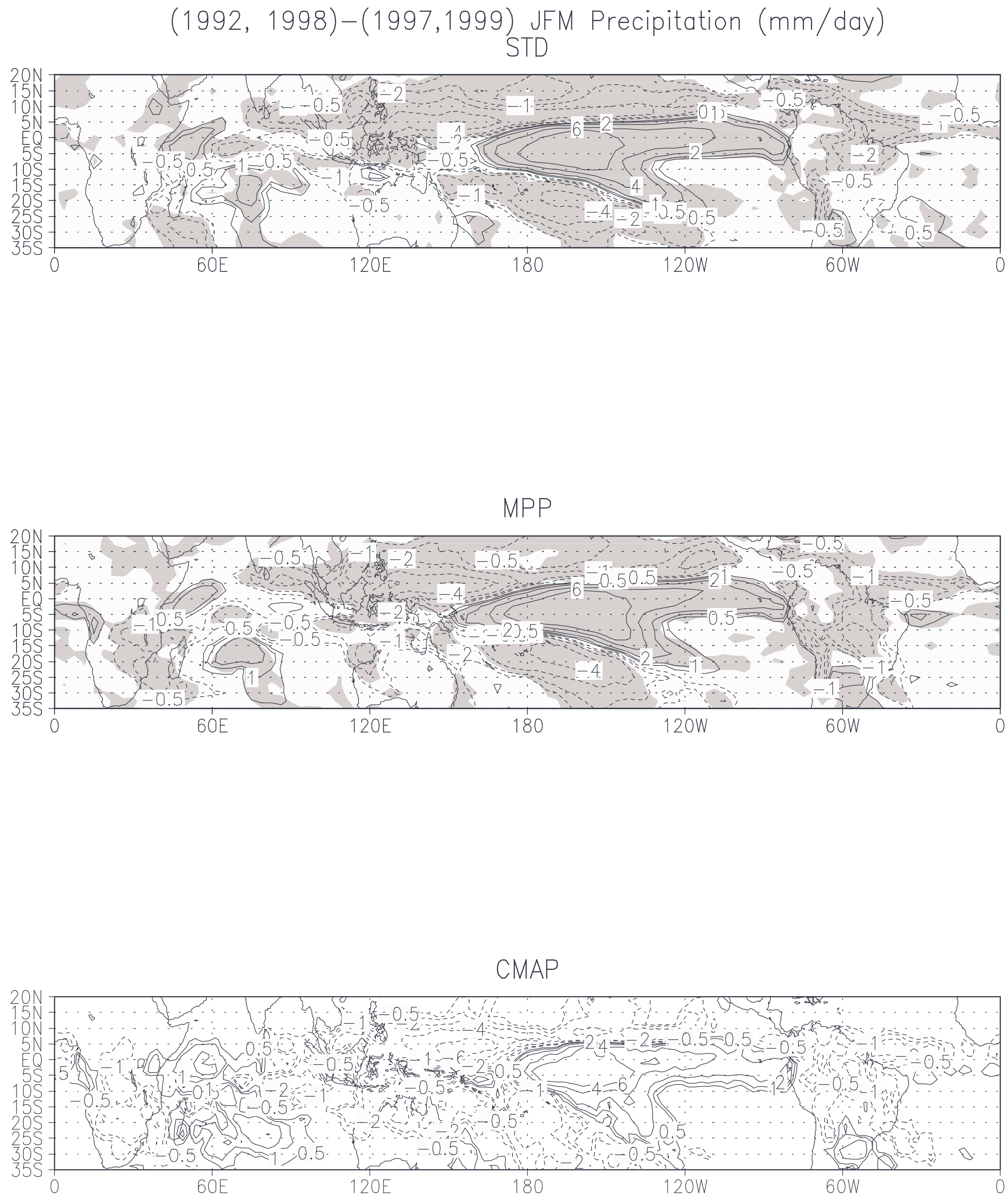


Figure 5: Difference in composite (El-Niño - La Niña) JFM precipitation. Shading indicates differences significant at the 95% confidence interval.

It can be seen that the observations (CMAP) show the expected negative anomaly over southern Africa whereas the STD version of the model demonstrates no anomaly. MPP however captures some of the negative anomaly over the eastern half of the sub-continent and the positive anomaly over the tropical western coast. These differences are significant at the 95% confidence level as indicated by the areas of grey shading. Further investigation of the model and observed precipitation using principal component analysis can be seen in Figure 6. The pattern of the first principal component of precipitation for the observations (CMAP) can be seen to be a characteristic TTT pattern extending from the continent into the south-west Indian Ocean. MPP can be seen to capture this pattern though the explained variance is about half that seen in the observations. The STD version of the model however explains less variance and the pattern is a truncated version of that seen in the observations, with only the oceanic section corresponding to observations. The variability over land is far less. The OLR patterns seen in the same figure are all similar. Although MPP does not capture the depth of the OLR pattern, it represents an amount of variance more comparable to observations than does STD. The timeseries of the first principal components shown in Figure 6 are given in Figure 7. It can be seen that for precipitation the MPP timeseries follows that of the observations better than the timeseries for STD. This is especially apparent in 1992 when the STD version of the model fails to capture the negative anomalies over the continent. The OLR timeseries is more chaotic and perhaps indicates that the clouds responsible for the rainfall anomalies may be modelled differently to those experienced in reality.

2.6 Discussion of HadAM3 modifications

Why MPP results in the observed warming of the atmosphere requires further investigation as there is a balance between radiative heating, latent heat release and sensible heat from the surface. Wilson and Ballard (1999) noted that MPP resulted in more high-altitude ice cloud and the reduced evaporation of rain. One possibility is that the latent heat associated with these ice clouds and reduced evaporation of rain is responsible for the warming of the troposphere and general increase in 500 hPa heights. However further diagnoses of clouds and radiative forcing are necessary before drawing firm conclusions. Figure 8 shows the difference MPP makes to the zonal equivalent potential temperature in the tropics (30°S-30°N). A negative gradient would indicate reduced stability and more convective activity whereas the positive gradient seen in figure 8 clearly shows that on average MPP reduces the potential for convection and results in increased stability of the tropical atmosphere. A similar plot of the global average (not shown) also indicates increased stability of the global atmosphere with MPP.

Generally the long-term JFM climatology of HadAM3 is improved using MPP. Most notably for our purposes the climatology in the region of southern Africa and adjoining Indian Ocean, during the main rainfall season, is closer to that observed in the NCEP reanalysis data. We have also demonstrated that dynamical differences are slight when MPP is introduced to the model. However, precipitation over the region is improved significantly. Thus, although most changes caused by MPP are small in comparison to the model biases, the dynamical response to SST anomalies is better and rainfall simulations made with the model more realistic.

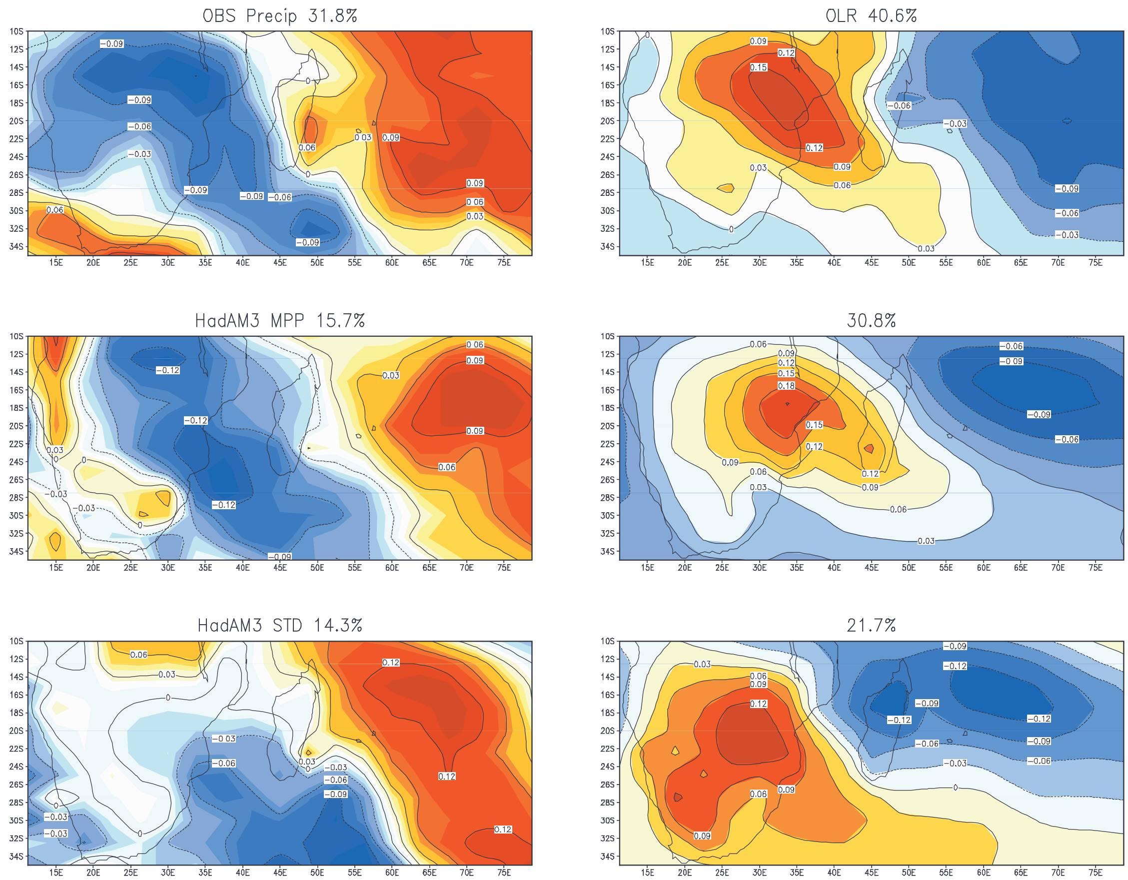


Figure 6: First principal component of precipitation (left) and outgoing longwave radiation (OLR) for Observations, MPP and STD. Variance explained is given above each plot.

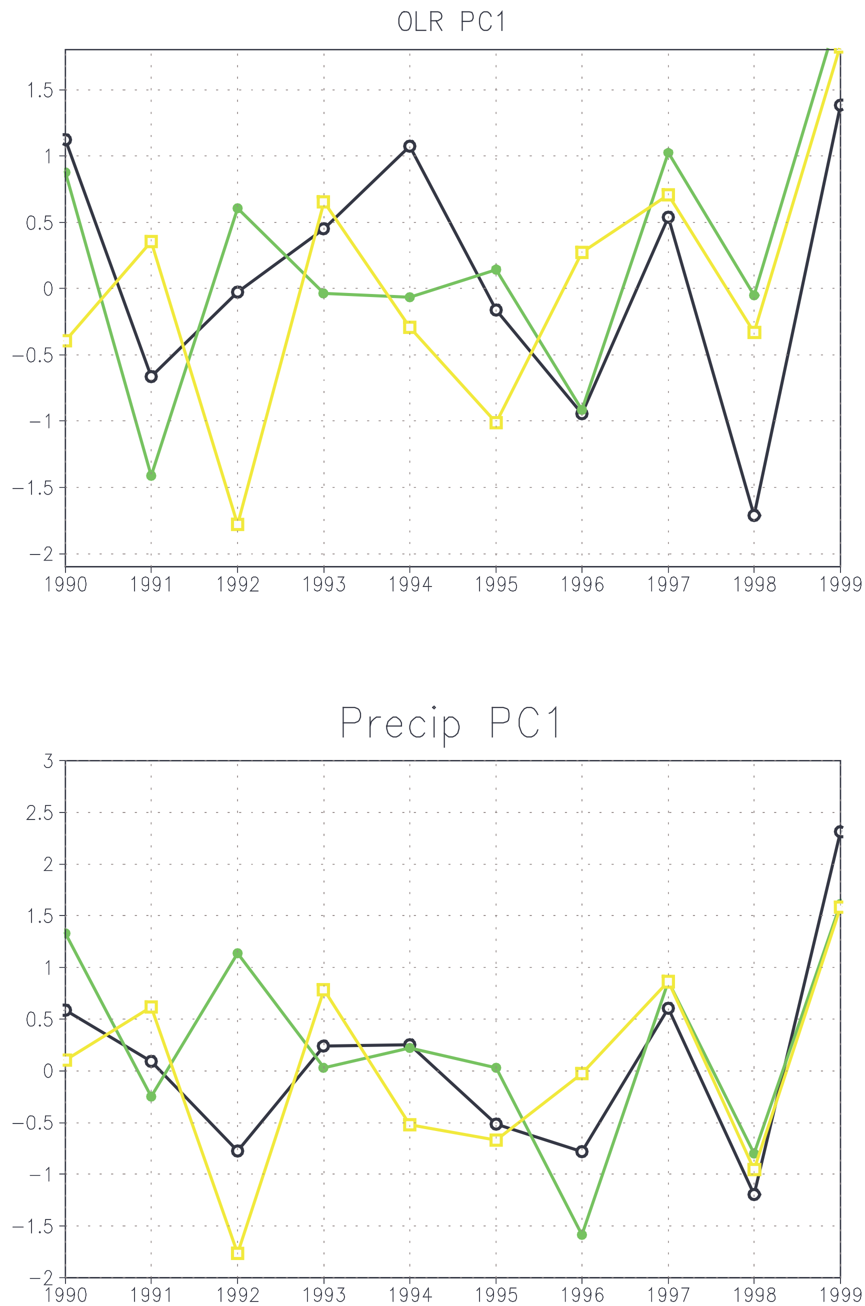


Figure 7: Time series of the first principal component of precipitation (bottom) and outgoing longwave radiation (top) for Observations (yellow), MPP (black) and STD (green).

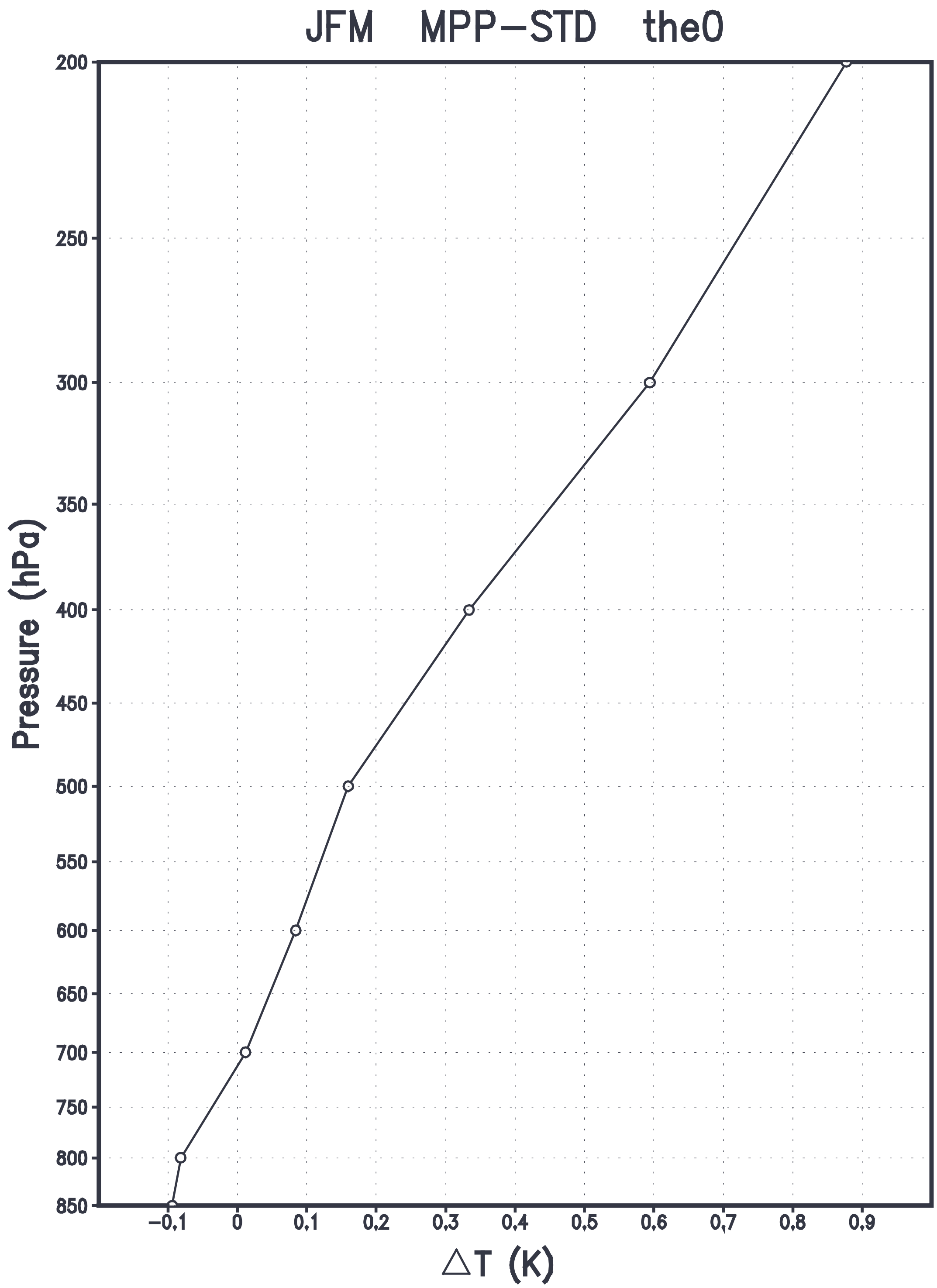


Figure 8: Vertical profile of the difference (MPP-STD) in zonal equivalent potential temperature (30°S-30°N).

2.7 GCM Baseline climate performance

Considerable work in recent years has been done to assess the skill and variability of atmospheric general circulation models (AGCMs). The Atmospheric Model Intercomparison Project (AMIP) began in 1989 (Gates, 1992) and has been useful in quantifying the ability of models to simulate the climate and to identify various shortcomings in the modelling. Armed with this information, model-based predictions of future climate scenarios or atmospheric sensitivity to lower-boundary forcing can be tagged with appropriate levels of confidence.

In this application we wish to assess the models at two levels. The first is how well the GCM simulates the observed general circulation and the underlying energy cycle. This facet deals with the overall performance of the model in simulating the broader aspects of the atmosphere. The second aspect is to probe into the higher-order variability of the daily circulationand to ascertain whether the statistics of this circulation are realistic or not. In other words, is the model simulating the correct synoptic-scale archetypes at the correct frequency and intensity? The timing of individual events is not so critical but the long-term average (e.g. seasonal or decadal) needs to be correct for the right reasons. Often time-averaged fields may look reasonable while daily circulation statistics can be very different from reality. Errors at small spatial scales are known to translate directly into errors in the large-scale circulation (Sperber et al., 2001) and are thus important to identify when trying to understand the shortcomings of a model. In addition, downscaling work through regional climate models is done by nesting these models within the GCMs. The transfer of data into the regional model domain through the lateral boundaries is done at a high temporal frequency, of the order of a few hours. If the GCM is not doing a good job of these higher-order frequencies then the regional model will also invariably suffer.

The baseline skill of the models considered here was determined by comparing the model simulations to the NCEP/NCAR reanalysis data (Kalnay et al., 1996), the latter being considered the best representation of reality available today. The spatial resolution of the three models and the NCEP/NCAR reanalyses are all roughly equivalent making direct comparisons credible. A comprehensive account of this assessment is published in Tennant (2003).

A novel way of investigating the ability of a model to simulate the general circulation is to look at fields of barotropic (vertical mean) and baroclinic (vertical shear) kinetic energy. In southern Africa, changes in these fields have been related to seasonal rainfall characteristics (Tennant and Hewitson, 2002; Tennant and Reason, 2004). The barotropic kinetic energy relates to the jet stream that is driven by angular momentum flux and energy transfer from baroclinic processes. The latter are primary mechanisms, active in the mid-latitudes, that transport excess solar energy from the tropics to the Polar Regions.

It was found that the GCMs have fairly large biases in their simulation of the current climate. Kinetic energy fields of the barotropic kinetic energy show that the models have varying errors in the strength and placement of the jet stream (Figure 9). All three models show a negative bias in the high latitudes around Antarctica and a positive bias north of that for the DJF season. This implies that the models simulate the southern hemisphere jet stream too far north and in some instances too intensely.

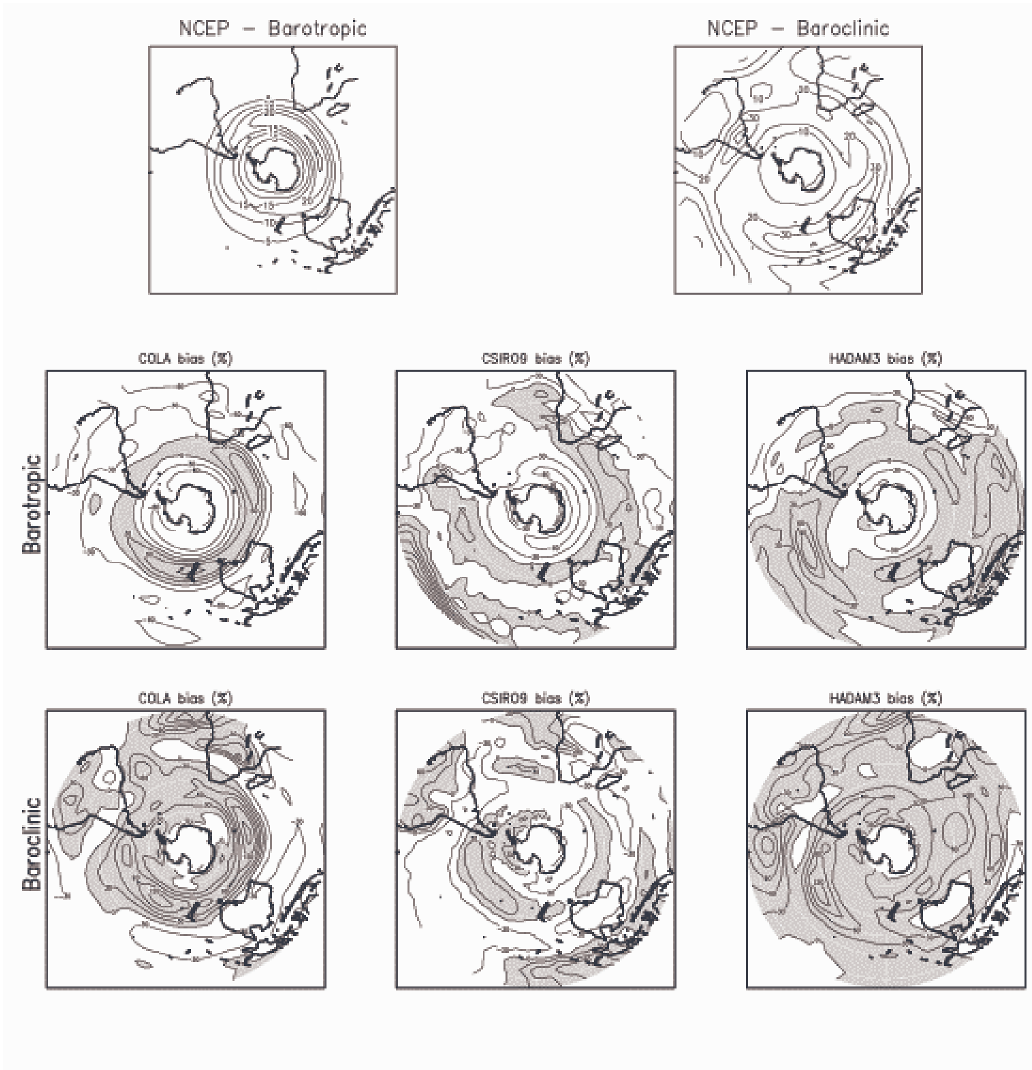


Figure 9: Barotropic and baroclinic kinetic energy for daily winds from NCEP/NCAR reanalysis (top row) and COLA, HADAM3 and CSIRO9 AGCM biases expressed as a percentage of the NCEP/NCAR values for DJF days from 1986 to 1998. Areas of positive bias are shaded.

The COLA model underestimates barotropic kinetic energy throughout the tropics and sub-tropics while CSIRO and HADAM models show a strong positive bias in the South Pacific Ocean. The baroclinic kinetic energy fields of all models also have fairly large biases. Again the acitivity in the mid-latitudes is exaggerated as is the tropical acitivty over South America, South Atlantic Ocean and Africa.

The model energy biases demonstrate that the errors in the representation of the atmosphere by these models are evident at a wide-range of spatial and temporal scales. The errors are typically brought about through incorrect incorporation of unresolved physical processes and unavoidable errors in atmospheric initial conditions.

2.8 Evaluation of SST forcing versus natural variability

Global SST patterns always exhibit some anomaly over some part of the world in any given period. As these anomalies are known to force variability in the atmosphere, it is useful to investigate what variability would be present in the (model) atmosphere without the presence of SST anomalies. This was done by comparing a 13-year simulation using climatological SSTs to the five simulations using observed SSTs.

The response of all models to SST forcing is clear when considering a pseudo-SOI (Figure 10). The La Niña event of 1988/89 and the El Niño events of 1991/92 and 1997/98 are shown with a strong signal. In this case the signal may be determined by the ensemble-spread, where a small spread indicates a strong signal and a large spread a weak signal. As expected, the simulation using climatological SSTs does not simulate these events (Figure 10), but yet the pseudo-SOI does vary during the period. In most cases this is constrained to one standard-deviation but there are events, particularly with CSIRO where the pseudo-SOI reaches two standard-deviations.

It is also instructive to investigate the effect of SST anomalies on atmospheric temporal variability. Figure 11 shows that 500hPa height variability is improved by 10 to 40% over the tropics and over the southern hemisphere convergence zones during the austral summer when using observed SSTs rather than climatological SSTs. The latter is most noticeable in the HADAM model. This result suggests that the variability in the atmosphere is forced to a significant degree by the SST anomalies and that a good representation of the SST field is a prerequisite for an atmospheric model.

2.9 Intra-seasonal variability

The Self-Organizing-Map (SOM) routine is used to evaluate the intra-seasonal variability of the models. This was done by submitting the daily NCEP energy fields to a self-organizing map routine and forming a pre-defined number of archetypes (nodes). For this application we chose a 7x5-node SOM which includes 35 distinct archetypes. The advantage of SOMs, over, say, cluster analysis, is that the SOM places similar archetypes near each other on the SOM so that the archetypes follow a smooth transition across the SOM and that the SOM attempts to represent the full variance structure in the data. This means that dominant archetypes of the circulation will be identified and not smoothed out by averaging. We also chose the 500hPa height field for this study as it represents mid-tropospheric processes and is a good proxy for the tropospheric circulation.

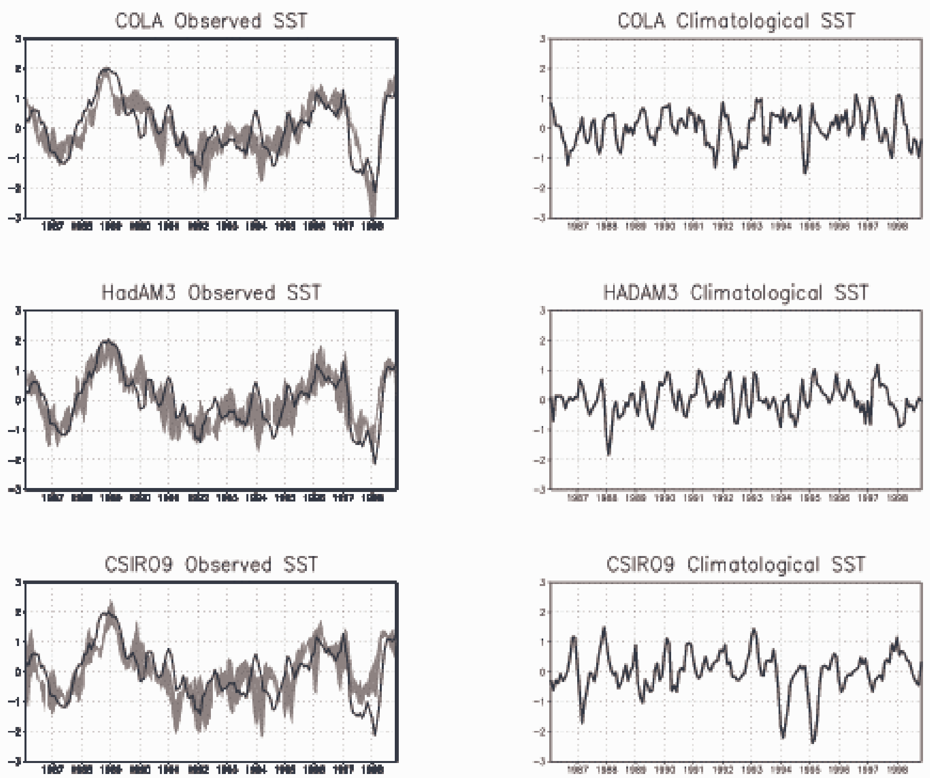


Figure 10: Pseudo-SOI series calculated using model grid boxes closest to Tahiti and Darwin. AGCM output using observed SSTs (gray shading indicates ensemble spread) and the solid black line the pseudo-SOI using NCEP/NCAR reanalysis data (left column). Output from the climatological SST simulation (right column).

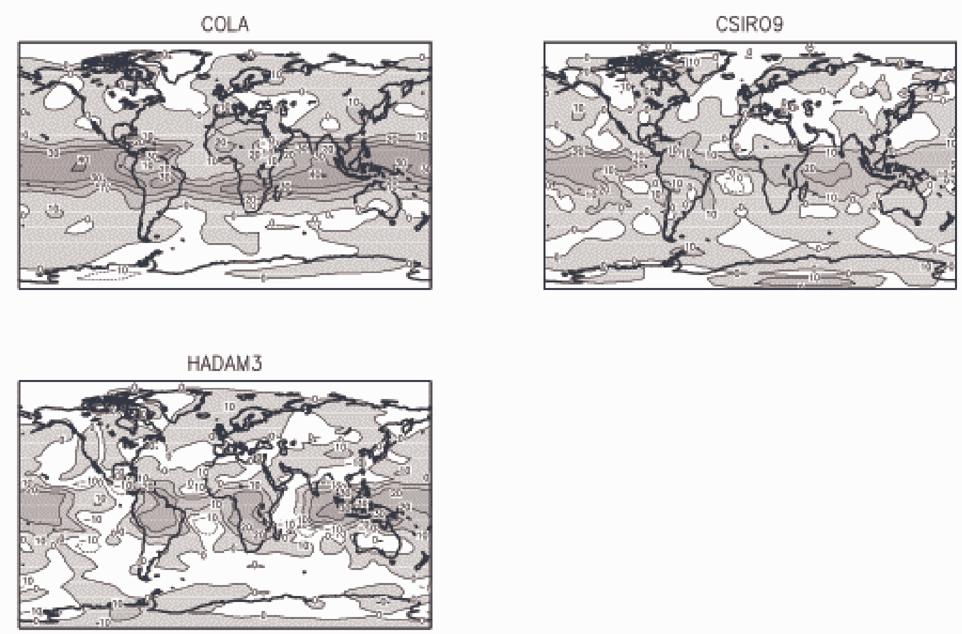


Figure 11: Percentage improvement of 500hPa height temporal variability when using observed SSTs relative to climatological SSTs in AGCM simulations

Once the SOM was trained using the daily 500hPa reanalysis data fields, each field from the reanalysis data and the three models were then each associated with a SOM node. Using this information a two-dimension histogram of the SOM node frequencies for each model could be compared to the NCEP histogram. The first striking result is that the frequency of archetypes of daily circulation of particularly the COLA model tends to be constrained to certain archetypes while simulating too few of another archetype (Figure 12). The particular node in question on the centre-right side of the SOM represents an archetype with the lowest spatial variance. The model also tends to underestimate the number of days with the strongest meridional gradient. This suggests that the COLA model is underestimating 500hPa variability. This is further supported by the fact that the COLA and CSIRO models underestimate the frequencies of nodes around the periphery of the SOM, as these represent the extremes of variability. The HADAM model produces a frequency histogram much more similar to NCEP, but still has some nodes with differences up to 44%. Notwithstanding, these differences do not show any particular spatial pattern and could simply be a small shift in one or two nodes around the SOM. This is not a serious issue as the patterns in adjacent nodes are similar.

2.10 Summary

GCMs clearly have differing strengths and weaknesses, but all models assessed are, nonetheless, skillful for the southern Africa domain and hence a valuable tool for investigating the climate system. With due recognition of the limitations, GCMs provide a credible simulation of the coupled climate system. For any given application the choice of model to be used requires assessment of the model; whether the model appropriately simulates the key dynamics of concern. In addition, the pragmatic issues of computational requirements of a particular model, the existing experience with the model, and whether the model has been adequately assessed will be compounding factors in undertaking a GCM-based study.

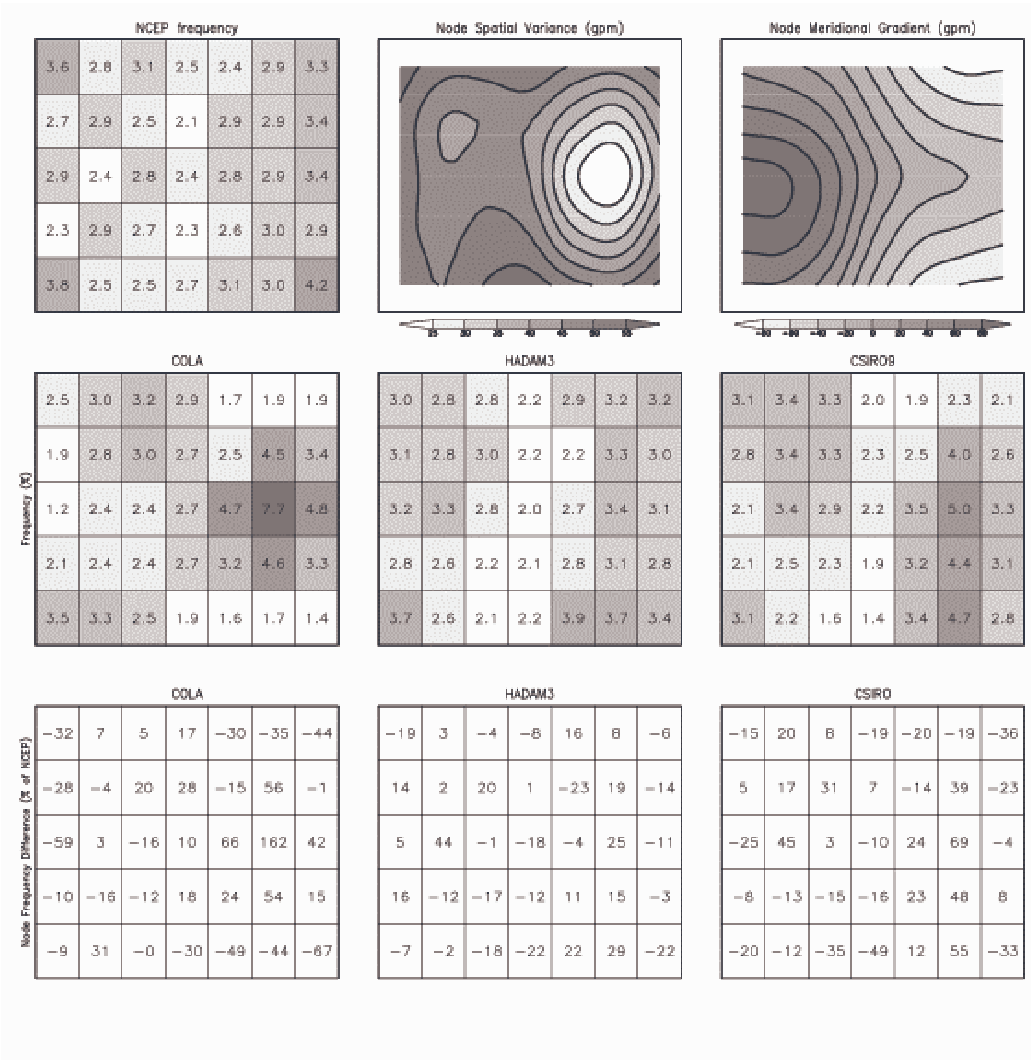


Figure 12: SOM-node frequency maps (middle row) and associated errors (bottom row) expressed as a percentage of NCEP/NCAR frequencies (top left) of the COLA, HADAM3, and CSIRO9 AGCMs for daily mean 500hPa heights from Jan 1986 to Dec 1998. Also shown are the two-dimensional histograms of within-node spatial variance (top middle) and meridional 500hPa contour gradient (top right)

3. Regional Climate Models

While GCMs are useful tools in understanding the atmospheric processes on a continental or hemispheric scale, those in use today have at most a spatial resolution of the order of 2.5º latitude by 3.75º longitude. Although these models are continuously being improved, reliable or detailed regional scale skillful resolution will unlikely be achieved in the near future using these models alone (Russo and Zack, 1997); especially considering the level of computational resources in southern Africa. Two options to address this shortcoming are available; firstly, variable resolution GCMs wherein the GCM grid is concentrated on a region of interest (although at the expense of resolution in other, possibly critical, global regions), and secondly, nested Regional Climate Models (RCMs) – limited domain models forced at their boundaries by GCM-derived data.

The necessity for either of these approaches stems in part from the needs of end users and decision makers, who often require information on these local scales and may even use the GCM data incorrectly extrapolating it onto the local scale, and from the core research question of investigating local and regional scale dynamics poorly resolved in the GCMs. Moving from GCM resolution to more regional scales is commonly termed downscaling, either empirically or as in this case, dynamical downscaling with a high-resolution model. The use of nested dynamical models was first proposed by Dickinson et al. (1989) and Giorgi (1990), and now is by far the dominant approach adopted world-wide.

The RCMs essentially use physics and parameterizations very similar to those of the GCM, but undertakes the simulation on a much finer scale. The RCMs thus have the capability of resolving smaller scale atmospheric processes and using this information to downscale large-scale synoptic fields. A second advantage is the ability to better resolve local-scale controls. Computationally, the use of RCMs is also more viable than GCMs and they allow the selection of a much smaller region of interest for study. The capability of these models to be nested with GCMs makes their use even more important especially in the context of downscaling climate change scenario data to regional scales.

Like GCMs, regional climate models also work on the principles of a set of governing physical and mathematical equations. These enable the models to represent most of the processes, interactions and feedbacks of the climate system that are present in the GCMs. The choice of the physics parameterization schemes used in the model has a large influence on the final results. These schemes therefore have to be tested for the region being modeled. Similarly the selection of the domain for modelling must be done with careful consideration of the region, the experimental design and the ultimate use of the RCM results (Giorgi and Mearn, 1999). The chosen domain should be large enough to allow the development of internal mesoscale circulations and also include all relevant regional forcings. The area of interest in the study should be placed well away from the buffer zone to prevent any noise from the boundary conditions affecting this region. These boundaries should also not be placed over complex terrain to avoid any noise caused by mismatching the coarse resolution driving data with the high resolution model topography. Modelling over complex orography has been tested in this project using an RCM.

Unlike GCMs, RCMs require lateral and surface boundary forcing. These input data can be either observed climate data (e.g. NCEP reanalyses) or nested within boundary data derived from a GCM. Further, given an initial state, a simulation period is required to develop the features internal to the RCM domain (spin-up). This 'spin-up' time can vary depending on the RCM, but is typically of the order of time required for passage of synoptic scale systems through the RCM domain; say 3 days for southern Africa. However, in climate-length simulations (multiple years) it is also important to allow sub-surface parameters such as the deep soil temperature and moisture conditions to equilibrate with the atmospheric forcing – a process that might require a year or more of spin up time.

The need to understand the potential impact and vulnerabilities posed by climate change has made the use of RCMs particularly more important. On the one hand it is imperative that we understand the role of local scale forcing such as land surface feedbacks if we are to appropriately understand the regional impact of global change. On the other hand, impact and vulnerability studies often require information on a scale that is not provided by GCMs. Downscaling of these climate change scenario data for such purposes is now of a high priority and the nesting of RCMs within GCMs plays an important role in this process. The operational running of an RCM in this nested mode is very similar to running the model using observational reanalysis data. The RCM in this case will use output produced by a larger scale GCM as initial and lateral boundary conditions.

There are a number of well established RCMs used today around the world for various studies. They all share the issues stated above but they also differ in other ways. At the University of Cape Town, two different RCMs are being used for modelling purposes. These are the PSU/NCAR Mesoscale Modelling System (MM5) and the PRECIS Modelling System.

3.1 The MM5 Regional Model

The MM5 limited area model was developed by Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR). In it’s most recent form it is a non-hydrostatic, finite difference, primitive equation model with a terrain following sigma level vertical coordinate system. As explored in subsequent sections, numerous parameterization options have been implemented for the boundary layer, cumulus cloud, explicit moisture and radiation processes. An advanced land surface/vegetation sub-model is included that predicts soil moisture and temperature as well as various vegetation atmosphere interactions including canopy water and transpiration. Multiple nesting capabilities including both two-way (where the internal domain can affect the outer forcing domain) and one-way nesting schemes (where the forcing domain receives no information from the internal domain). Choices related to each of these issues, as for all RCMs, can result in markedly different simulation skill.

The MM5 model has been widely assessed in part as a result of extensive application for real-time weather forecasting as well as for climate downscaling.

3.2 The PRECIS Modelling system

The PRECIS model is a new regional climate model developed by the Hadley Centre in the UK. This model is based on the HadRM3 model and has been developed to be a PC-based RCM used by less developed countries as a tool in making their own predictions of climate change on a local scale (Wilson et al., 2003). The model has 19 vertical levels. The bottom 4 atmospheric levels are purely terrain following and the top 3 levels are purely pressure levels. The intervening sigma levels are a linear combination of both. The model can be used with a horizontal resolution of up to 25km although only the 50km resolution has been tested thus far in this project. The model is set on a rotated pole projection grid ensuring that the RCM grid boxes are quasi-regular in area. Default boundary conditions are pre-supplied by the Hadley Centre (either the ERA-15 data or data from their HadAM3P model), limiting the basic versatility of the model for a range of applications.

3.3 Land surface sensitivity experiments

One of the most valuable attributes of RCMs is their use to explore fundamental attributes of the regional climate system. In this regard there remain large unknowns for southern Africa, not the least of which is the role of the land surface in modulating climate variability. Since the early work of Charney (1975) on land-atmosphere feedback in the Sahel region, there has been an increasing awareness of the complex interaction between the land surface and the atmosphere (see Pielke, 2001 for a review). Important land-surface parameters that influence the climate include albedo, soil moisture and leaf area index (LAI). LAI also affects evaporation and hence latent heat fluxes at the surface, while albedo particularly influences surface temperature and specific heat fluxes. Since fluxes of water, energy, momentum and carbon dioxide at the land-surface are regulated by plant physiology and structure, vegetation distribution is an important consideration when evaluating land-surface climatology. Recent developments in coupling land-surface models (LSMs) and regional climate models have helped to improve model simulations, but there is still scope for further improvement. Two potential avenues of development exist:

- improving the numerical simulation of land surface processes and their interaction with the atmosphere, and
- more accurately describing the regional land-surface in terms of vegetation, soil and hydrological parameters.

While much work has been done on developing accurate and comprehensive land surface datasets for the Northern Hemisphere only limited work has been done for the African continent. Most of this work has involved deriving vegetation parameters from satellite data sets (Mamoudou and Frouin, 2001; Wang et al., 2004).

For sensitivity studies, RCMs are unique in their ability to simulate the atmospheric response to either boundary or internal perturbations to the climate system. Thus, in this application the RCM is used to explore the model-simulated atmospheric sensitivity to 1) uniform changes in albedo and soil moisture, and 2) the use of an alternative map of vegetation distribution, which would effectively change albedo and other land-surface parameters in a non-uniform, but more realistic way.

The sensitivity of the atmosphere to these parameters is of great interest for two reasons. The first is that it gives us some idea of the importance of accurately determining these parameters in a model. If the atmospheric sensitivity to these parameters is small then our margin of error in specifying them can be large. However, if the sensitivity is large then we need to specify these parameters very accurately. The second reason why addressing these issues is important is that these two parameters change radically both inter seasonally and inter annually, and critically, will likely be highly responsive to climate change. Greening and wilting of vegetation can change the albedo by up to 50%, and similarly, soil moisture can change radically between seasons and from year to year. While the near surface soil moisture might respond rapidly to precipitation, deeper soil levels respond much slower and a dry season can result in much reduced moisture availability for the following season.

3.3.1 Albedo Sensitivity Experiment

The importance of albedo has been recognised for many years (Charney, 1975) and has been the focus of many GCM based sensitivity studies (Berbet and Meire, 2003; Lofgren and Brent, 1995) The objective of these experiments are to determine the RCM simulated atmospheric sensitivity to changes in albedo, soil moisture and vegetation over the African subcontinent.

The MM5 regional climate model was used for this experiment. The standard model allows different land-surface datasets to be used, however the only data that covers Africa is based on the United States Geological survey (USGS) global vegetation dataset. Analysis of this data indicates that in many areas of Southern Africa it is inaccurate, although as a very general view of the land surface it is usable for this experiment. Other work discussed later in this report seeks to improve this dataset over Southern Africa.

The land-surface model (LSM) used in the experiment is called NOAH and it is derived from the PSU LSM (Chen and Dudhia 2001). This model predicts soil moisture at four different soil levels as well as the overlying canopy water. Various vegetation parameters are used in the modelling of transpiration and other moisture and heat fluxes regulated by vegetation. Surface evaporation and runoff are also modelled. The NOAH model integrates with the atmospheric model through a parameterization of the atmospheric boundary layer. The vegetation roughness length is particularly important in determining boundary layer friction and hence mixing depth in the atmospheric boundary layer. Roughness length can also have a significant impact on a region’s climate and this is a possible future avenue of research for the southern African area.

The first experiment involved perturbing the albedo parameter. Instead of trying to change albedo in a way that resembles observable perturbations it was decided that a series of broad-scale perturbations should initially be applied across the whole domain. While it is accepted that this does not resemble the kind of albedo changes observed in reality, it does provide a simple perturbation that allows an easier diagnosis of the sensitivity of the atmospheric response.

Two separate experiments were carried out. In the first a broad-scale increase in albedo by 20% was applied for the summer season of 1998. Analysis of the results of this experiment suggested that further experiments should be performed to further understand the complex feedbacks involved. The subsequent experiments are still ongoing and form part of post-project research in light of the revealed importance of the role of the land surface. Only the preliminary results will be discussed here. These experiments involve perturbations of both increases and decreases of albedo of 30% and 15%. While continuing work will involve running model integrations for multiple seasons including a wet season, a dry season and a neutral season, at this stage only one season has been integrated. The summer season of 1991/92 was chosen (as representative of a dry season) and the model was integrated starting in November and finishing at the end of February. Only December, January and February were analysed to make sure that any model spin up would not be included in the analysis.

The results from the first experiment involving the 20% increase in albedo proved to be surprising. Plotting the anomalies of surface temperature between the control and perturbation results reveal that very significant temperature changes are observable over large parts of the model domain – comparable to temperatures differences between a hot versus normal season (see Figure 13). However, rather than an inverse relationship between albedo and surface temperature as might be expected, many areas in the interior of the continent indicate a positive relationship between albedo and temperature. The results demonstrate that albedo changes as small as 20% (within natural variability) can result in surface temperature changes of the seasonal mean by nearly a ºC.

In order for surface temperatures to increase, either latent heat flux due to evaporation must decrease, sensible heat flux to the atmosphere/ground decrease, or incoming shortwave radiation must increase. Anomalies in soil moisture do not show marked changes in the simulation. However changes in incoming shortwave radiation do show a strong pattern that matches that of the surface temperature changes. This suggest that the increase in temperature is a result of increasing radiative heating at the surface, resulting from a decrease in cloud cover.

Decreasing cloud cover would suggest a reduction in atmospheric moisture, and the anomalies of atmospheric specific humidity confirm this (Figure 14). While increasing surface temperatures would suggest greater evaporation (subject to surface moisture availability) and hence potentially more atmospheric moisture, this is not the dominant source of moisture for the area. The reduction in moisture must be resulting from a reduction in moisture transport into the interior regions of the continent. The only possible explanation for this change in moisture transport would then be a change in the regional scale circulation as a consequence of albedo forcing. Once again, a contradiction seems to be apparent. Increasing temperatures in the interior of the continent would suggest a strong thermal trough, which in turn would suggest stronger continental convergence drawing moisture from the coastal areas into the interior. The results however indicate otherwise.

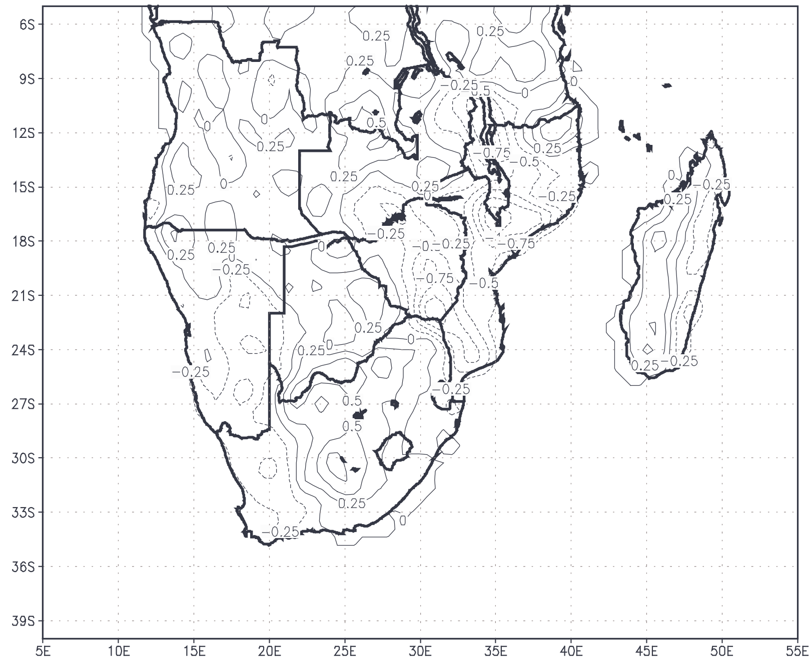


Figure 13: Seasonal mean ground temperature anomaly (°C) resulting from 20% broad albedo increase.

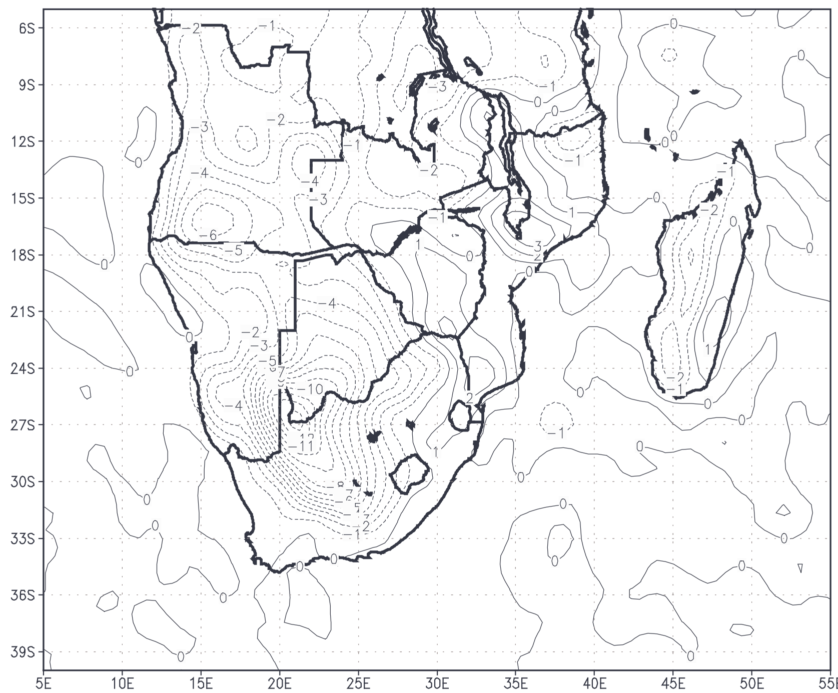


Figure 14: Percentage change in specific humidity resulting from 20 percent increase in albedo.

A possible dynamical explanation for this is that cooling over the eastern escarpment results in reduced moisture uplift through convective processes and hence reduced transport of moisture in elevated layers of the atmosphere over the high escarpment. However, the reason for the escarpment cooling is not clear. This reduction in moisture transport into the interior of the continent results in reduced cloud cover, increased incoming solar radiation, and hence increased surface temperatures. While this is a possibly simplistic explanation and needs further investigation it does indicate the kinds of complex feedbacks that can occur between the land surface and the atmosphere. What is perhaps more concerning is the possible positive feedback increased temperatures and reduced rainfall could have on the albedo. Regional climate modelling is currently the only way these kinds of complex systems and feedbacks can be investigated.

The results from the second set of experiments are still very preliminary. However, they do suggest that the atmospheric response and feedbacks are even more complicated than the first experiment suggested. In the 1991/92 summer season, increasing albedo by 30% resulted in large areas in the west of the country as well as over Mozambique showing strong cooling while the Congo basin shows strong heating. Decreasing albedo by 30% shows a similar, but obviously opposite, response though the magnitude of the response is smaller.

It must be noted that the second set of experiments used a different model configuration, including a different convective cloud scheme and boundary layer scheme as a result of investigations into model physics and parameterization options (see later). This second convective cloud scheme does seem to simulate the diurnal cycle of cloud and precipitation much more realistically especially in the tropical regions. In addition the new simulations use an increased albedo perturbation of 30%. Consequently it is possible that the new (better) parameterizations and physics are responsible for the changes in regional response. Alternatively, it is possible that the increased albedo perturbation forced the climate processes beyond a threshold in the complex feedbacks. This highlights the importance of model development in ensuring that the results of model experiments are robust, usable, and account for the complexity of the regional dynamics of the climate system. Further work is crucially needed on this topic given that climate change will very likely impact regional albedos.

3.3.2 Vegetation sensitivity experiments

In light of the above work, realistic representation of the land-surface vegetation in response to climate forcing is all the more important. The complex nature of the biosphere makes it a challenging system to understand. Simple mathematical models have shed light on ecological processes and principles, and provide a convenient, but limited, representation of reality. More complex models have evolved in the form of process-based biogeographical and biogeochemical models, which incorporate detailed representations of plant growth and competition, chemical cycling and hydrology.

The two principal types of these complex models are static or equilibrium models and dynamic models (see Peng, 2000 for a review). Equilibrium models are designed to compute a vegetation state that would exist given a particular climatic state. Dynamic models have the advantage of being able to simulate transient changes in vegetation in response to external forcing (eg. climate change). Relative changes in the distribution of plant life forms or plant functional types (PFT's) can be predicted based on environmental constraints (Peng, 2000).

This study uses the Sheffield Dynamic Global Vegetation Model (SDGVM) to provide land-surface boundary conditions for the MM5 regional climate model. SDGVM supplies alternative vegetation characteristics to the default ones as used by MM5 and offers attractive possibilities for interactive coupling between the RCM and the vegetation model.

Developed by Woodward et al. (1995), SDGVM predicts potential natural vegetation according to the input variables of precipitation, temperature, relative humidity, CO_2 and soil texture. The model includes subroutines for biomass, phenology (the seasonal emergence and shedding of leaves), hydrology, carbon and nitrogen cycling, and dynamics (ie. transition between vegetation states). Disturbance by fire is an important controlling process in vegetation distribution (Bond and van Wilgen, 1996; Bond et al., 2003). For this reason, an approximation of the occurrence of fire, and its impacts on vegetation, has been incorporated into the model. Vegetation type is given in terms of plant functional types (PFTs). SDGVM defines 6 such types, namely C3 and C4 grasses, evergreen broad- and needleleaf trees, and deciduous broad and needle leaf trees. There is a 7th category assigned to bare ground. It is important to note that the model predicts potential natural vegetation, so the influence of agriculture and other human land-use activities are not considered.

Using SDGVM, a control vegetation state for southern Africa was computed. The climate input variables were provided by the University of East Anglia Climate Research Unit 0.5° resolution land-surface climate data for 1901-2000 (New et al. 2000). The SDGVM simulated average vegetation state for the years 1971-2000 are then used as the land-surface climatology for MM5. For ease of comparison with other data and for the incorporation of the information into MM5, the distribution of PFTs as given by SDGVM was reclassified in order to approximate the commonly identified vegetation biomes used by MM5. As with all models, SDGVM is imperfect, so discrepancies in its output when compared to observations of vegetation distribution are evident, but for the most part the model captures the general distribution of southern Africa's vegetation particularly well. If it can be assumed that the above vegetation distribution represents a plausible undisturbed natural vegetation state, then it follows that the difference between this distribution and present-day observations of land-surface conditions is largely attributable to the impact of human activities.

Figure 15 shows the SDGVM output in comparison to the United States Geological Survey (USGS) land-surface map as used by MM5. To assess the sensitivity of regional atmospheric circulation to these different vegetation distributions, two MM5 integrations were run. One used the default USGS map, whereas in the other this map was replaced by the SDGVM distribution. The simulations were run from 1 November 1984 to 28 February 1985 – representing a climatologically neutral summer period. To give an idea of the robustness of the results, a “mini-ensemble” was created by performing a second pair of runs identical to the above, but starting one day later (ie. with different initial conditions).

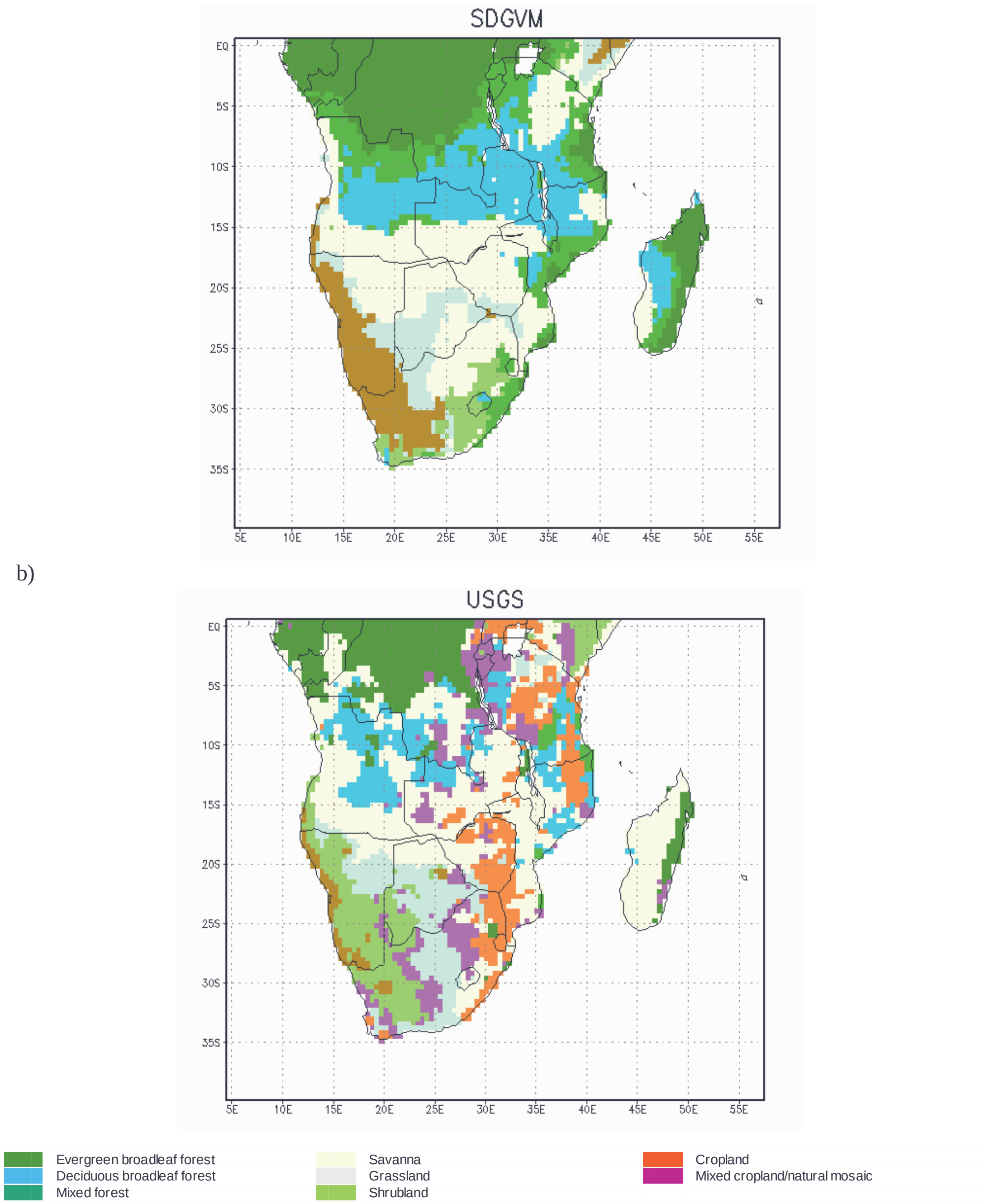


Figure 15: a) Potential natural vegetation as simulated by the Sheffield Dynamic Global Vegetation Model (SDGVM) and b) the United States Geological Survey (USGS) land-surface classification. Note agricultural land-use classes are not represented by SDGVM. Also evident in the SDGVM distribution is the greater extent dominated by forests and the lack of shrubland cover in the south-western regions. An important consideration, however, is that although the USGS data represent satellite observations, the assumptions and caveats associated with deriving vegetation parameters from satellite imagery ensure that this is not necessarily the most accurate representation of the region's vegetation.

The runs have been named U1, U2, S1 and S2 – U or S denoting USGS or SDGVM land-surface and 1 or 2 denoting initial conditions (1 or 2 November 1984) respectively.

Seasonal mean (DJF) anomalies were computed for selected atmospheric variables by subtracting S1-U1, S1-U2, S2-U1 and S2-U2. For 2-metre air temperature (T_{2m}), latent heat flux (LH) and specific heat flux (SH) the anomalies are consistent for all ensemble members, but for convective precipitation (P_{con}) the results are noisy.

Figure 16 shows the ensemble mean anomaly of T_{2m}. Cooling of between 0.5ºC and 1ºC is seen over central and northern Botswana, extending into south-eastern Angola. A general warming is experienced by the eastern parts of the sub-continent, with a maximum of up to 2ºC in northern Mozambique and Malawi. Latent heat flux anomalies (Figure 17) follow similar patterns to T_{2m}. Positive anomalies of up to $20Wm^{-2}$ are seen over most of Botswana and the Kalahari. This is consistent with the lowered temperatures since a greater LH implies more evaporative cooling and thus lower surface temperatures. Likewise, negative LH anomalies (of up to $30Wm^{-2}$) correspond to the regions of positive temperature anomalies. Specific heat flux anomalies (Figure 18) are generally weaker than those for LH, but are spatially consistent with the latter: negative LH anomalies correspond to positive SH anomalies and vice versa.

Relationships between these anomalies and the differences in vegetation characteristics are not readily apparent, but some deductions can be made. The areas of warming and reduced evaporation seem to correspond to a greater dominance of trees in the SDGVM distribution as opposed to the extensive agricultural regions shown in the USGS data. An initial interpretation of this result may be that more widespread forests would result in a darker land surface and thus reduced albedo, hence higher temperatures. However, one would also expect denser vegetation to intercept more precipitation in its canopy and transport more moisture from the soil to the atmosphere through transpiration, thus increasing the potential for evaporative cooling. In addition, it is seen in the results that the areas of cooling do not correspond with large differences in the land surface characteristics. This suggests a connection with regional horizontal circulation features.

The response of P_{con} (Figure 19) is very noisy, with anomalies of over $5mm.day^{-1}$ occurring over parts of the Indian Ocean and Madagascar. Over the sub-continent there appears to be little spatial correlation between precipitation and the surface moisture fluxes inferred from the LH plot.

This experiment has demonstrated that different representations of vegetation in an RCM can result in significant anomalies in climate parameters. In this case surface temperature, for example, varies by up to 2ºC. This demonstrates the importance of land-surface representation in regional climate modelling and confirms the need for ongoing improvements.

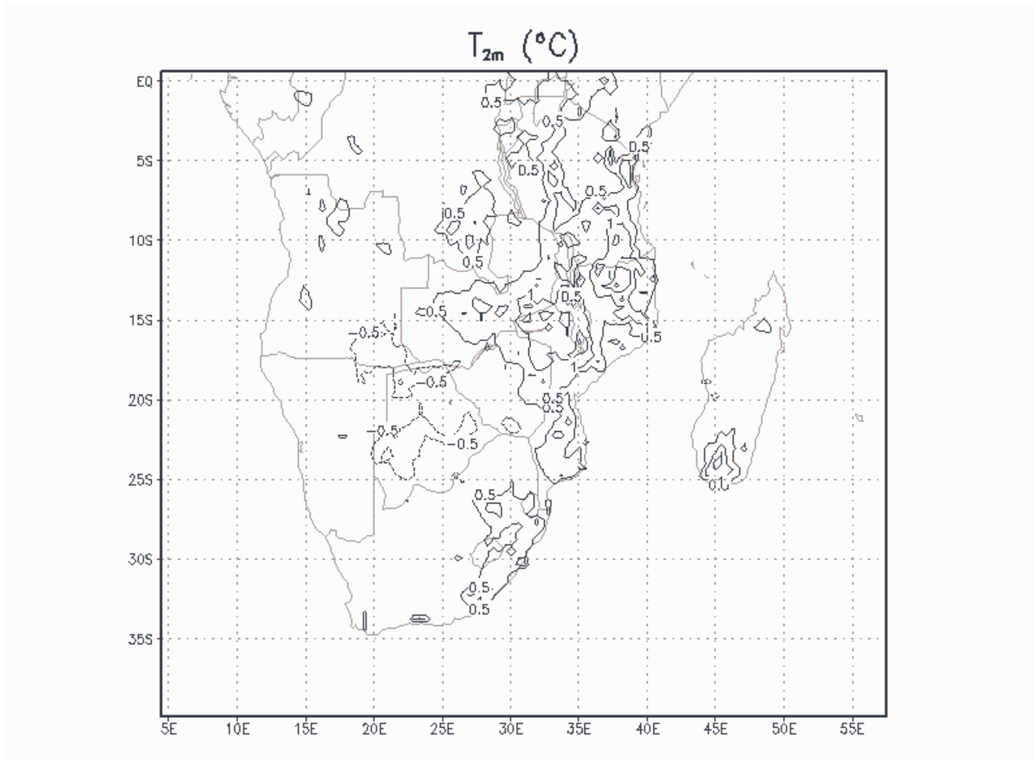


Figure 16: Ensemble mean anomaly of 2m air temperature for DJF (SDGVM land-use less USGS land-use). There is a general warming in the eastern parts of the sub-continent and a cooling over Botswana and south-eastern Angola.

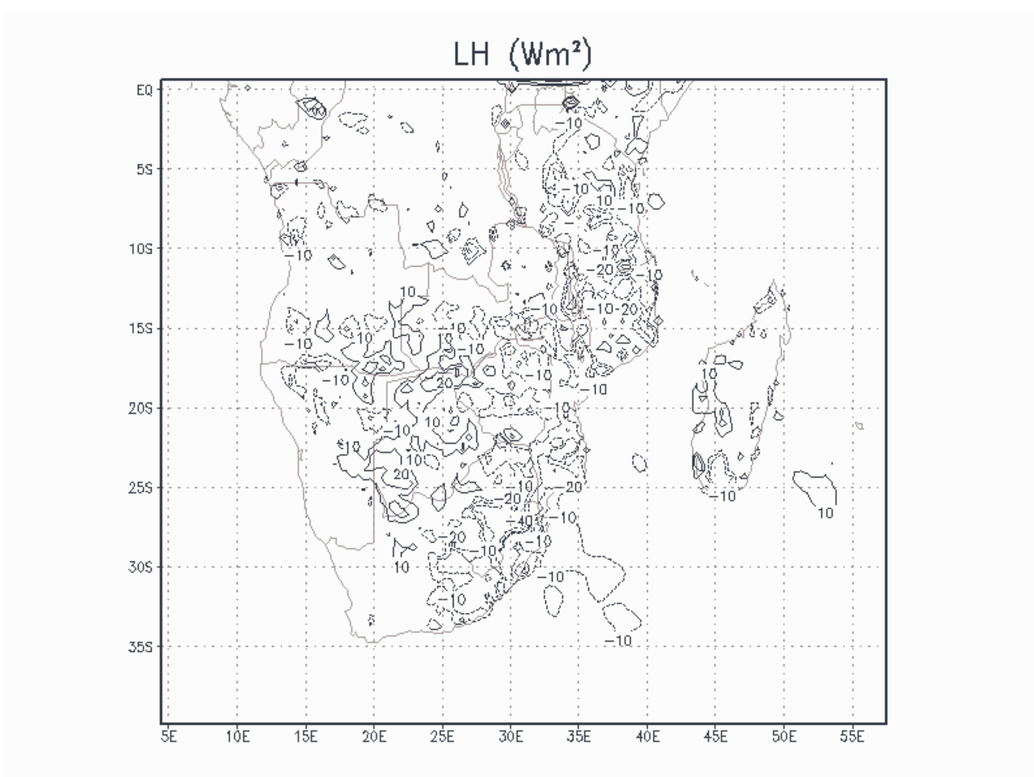


Figure 17: Same as Figure 16, but for latent heat flux. Negative LH anomalies are generally associated with the warmer temperatures in Figure x2 and vice versa.

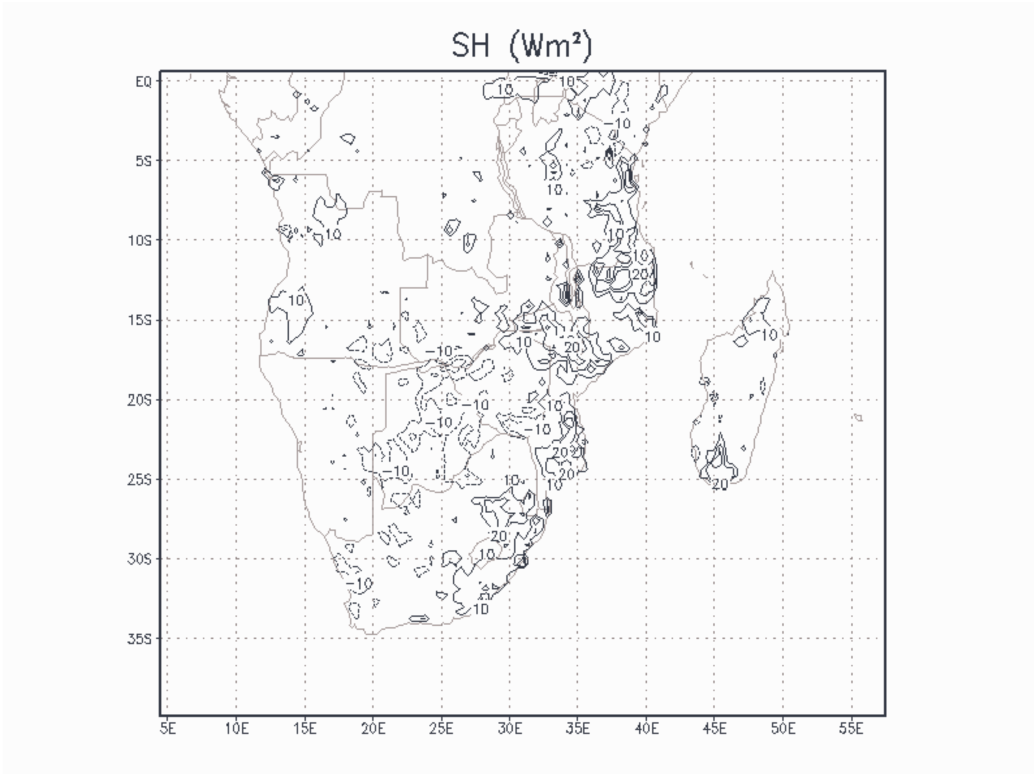


Figure 18: Same as Figure 16, but for sensible heat flux. The spatial patterns of these anomalies are consistent with LH and T_{2m}.

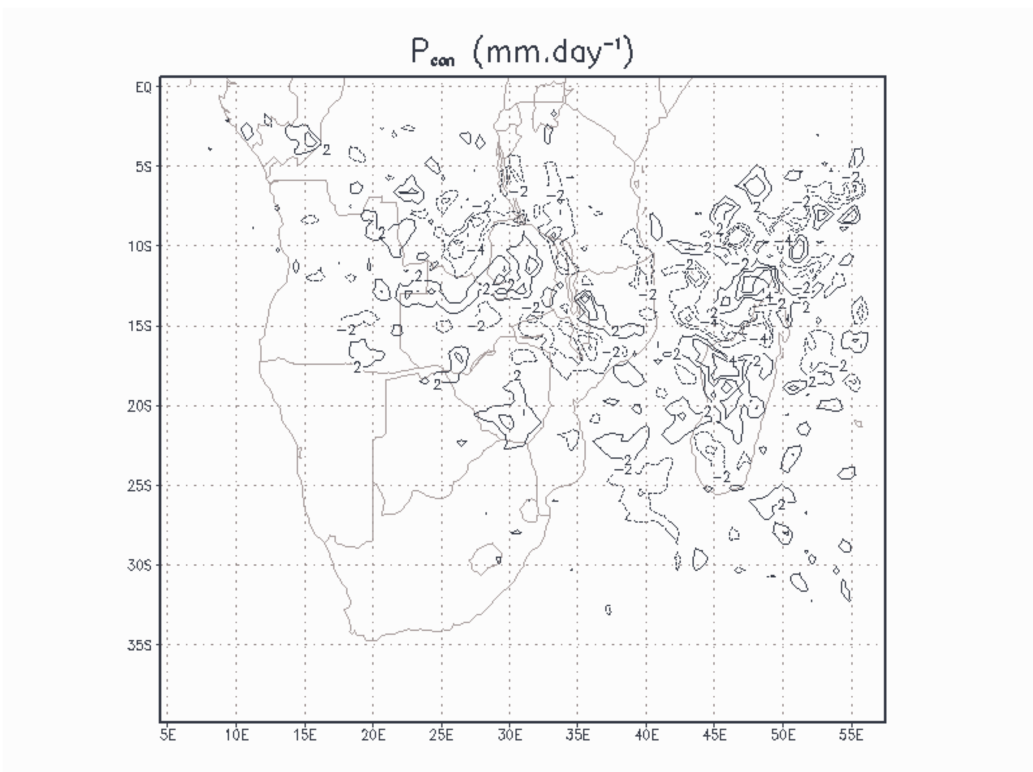


Figure 19: Same as Figure 16, but for convective precipitation. The response is noisy compared to the consistent patterns of $T_{2m,}$ LH and SH. The variation between ensemble members is large, so this result should be treated with caution.

3.4 Soil moisture experiments

Two preliminary studies have been undertaken to assess the key question of the regional feedbacks of soil moisture. In the first the MM5 model is used with perturbed soil moistures at wilting point and at field capacity. In the second the RegCM3 regional climate model is used with soil moisture help at 25% and 75% of saturation. The latter work was undertaken by the internship of one project participant (M. Mdoka) at the International Centre for Theoretical Physics (ITCP) in Trieste.

Both studies are exploratory and seek to simply gain some insight into the potential sensitivity of the models to soil moisture. This is an essential pre-cursor to further climate change studies where the soil moisture feedback could be a potentially critical feedback mechanism in moderating or exacerbating the regional impact of the global change forcing. In addition, is is speculated that soil moisture could be an important attribute in modulating intra-seasonal variability. At present very little is understood about this feedback mechanism.

The MM5-based simulations (New et al., 2003) were simple perturbations where the soil moisture was set to wilting point (nominally 25%) and saturation respectively. The model was then run for the duration of the 1997-1998 summer season for each of the soil moisture states. An additional simulation was completed allowing the soil moisture to freely interact with the atmospheric forcing. The results for the two runs in comparison indicate a strong sensitivity by the regional climate to the soil moisture. Figure 20 shows, for example, the surface air temperature response to anomalously dry soils, indicating anomalies of up to 4ºC for the seasonal mean; an anomaly of notably greater magnitude than that projected by global climate change. The concerning factor here is that the feedback appears to be positive which suggests that global warming could regionally be exacerbated by this feedback mechanism.

With regard to precipitation the strongest response is in the convective rainfall. For the other model parameters, the general indications indicated by the simulations for a dry soil (essentially reversed for a wet soil) include:

- reduced evaporation
- enhanced sensible heating
- tendency toward cyclonic circulation
- southerly moisture advection

These experiments are for only one season, and are currently being repeated for additional seasons, a broader range of soil moisture perturbations, and using optimized choices for the physics and parameterization options in the model.

The experiments with the RegCM3 model focused on determining whether the model can simulate variability between the driest and wettest periods and to assess the response of the climate model to changes in soil moisture and the associated feedbacks. The RegCM3 model is a derivative of the MM5 model, and development led by Dr. F. Giorgi at ICTP. For the most part the RegCM3 comprises a selected subset of the MM5 options along with refinements focused specifically on long term climate simulation. For this experiment the years 1991/92 and 1982/83 (driest seasons), 1999/00 and 1995/96 (wettest seasons) and 1983/84 and

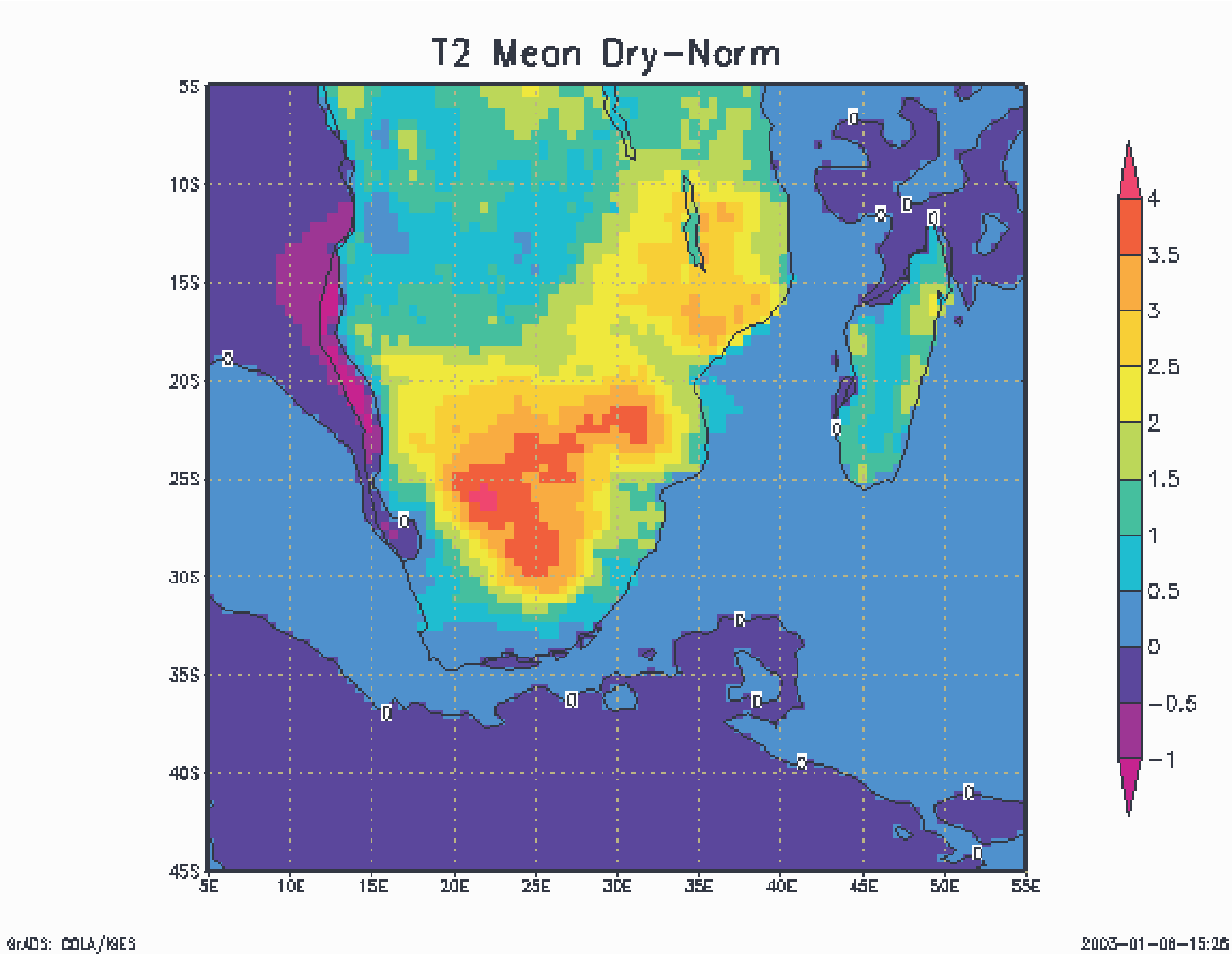


Figure 20: Mean DJF surface air temperature anomaly for the dry soil simulation versus the unconstrained soil moisture simulation.

1990/91 (normal seasons) were chosen for the simulation experiments. The experiments were conducted under the supervision of Dr. Giorgi at ITCP.

The RegCM3 was forced with NCEP reanalysis data, and used 60km resolution on a grid over southern Africa comparable to the MM5 domain already presented. The default model settings resulted in too much precipitation over the region as compared to the available daily rainfall data and the CRU and CMAP data, and several experiments were then carried out to try and fine-tune the model physics. Some of the parameters altered included realistic changes to the threshold values at which rain forms in the cloud, reduction of the Convective Available Potential Energy (CAPE) within the Fritsch-Chappell closure system, increasing the raindrop re-evaporation rate, changing the cooling rate of convection, and reducing the rate at which precipitation forms from the clouds. These changes resulted in different effects on the spatial distribution of precipitation, with some areas drying and other regions increasing in wetness. The selected configuration was for an increase in the re-evaporation rate of rain, whilst maintaining the other default settings within the Grell cumulus parameterization scheme.

Simulations to exhibit the effects/feedbacks of the modifications on the soil moisture conditions (wet,normal,dry) were carried out. The experiments were designed such that the model was initialised with 75% and 25% soil moisture for wet and dry conditions respectively. The simulations were done with the soil moisture being fixed at the two values throughout the simulation period. A control simulation for comparison used the same model configuration but allowed the soil moisture to be interactive with the climate.

Preliminary results show that most of Zimbabwe, Zambia and DRC are sensitive to soil moisture changes whilst the western parts of the region are less responsive. These regions are in broad agreement with the sensitivity to temperature shown by the MM5 experiments. With regards to precipitation, the RegCM3 precipitates too much rainfall over Southern Africa although it is able to capture the inter-annual variability and associated wet and dry conditions. However, more simulations are required to check on the sensitivity of the RegCM3 model by looking at a drier and normal season for the feedbacks experiments.

3.5 Response to SST dipole patterns

Studies have suggested that the Indian Ocean has influence on the climate of Southern Africa, and particularly, that the southern subtropical Indian Ocean SST anomaly dipole pattern may play a role in influencing Southern African summer rainfall. A number of observational and GCM studies provide strong evidence of interannual variability of sea surface temperature (SST) in the Indian Ocean and the link with observed rainfall variability over southern Africa. Most recently, Behera and Yamagata (2001) and Reason (2001) have presented observational and modelling evidence that a dipole-like pattern in subtropical South Indian Ocean SST is important for southern African summer rainfall for a region stretching southeast from Zambia towards the southeast coast of South Africa.

In this study, GISST2.3b data set is used to identify subtropical dipole events and a regional climate model, MM5 forced with NCEP reanalysis, is used to investigate atmospheric circulation over the southern Indian Ocean and Africa associated with two strong events (1981 and 1998) of opposite sign for the above phenomenon. The model is configured with standard default options with a 60km grid over a large a domain extending from the equator to 45ºS and from 5ºW to 75ºE. An ensemble of five different simulations, each initialised from a different time on November 30 / December 1 of the preceding year, was performed for each of the 1981 and 1998 cases.

Detailed results may be found in the thesis of Hansingo (2004). In general, MM5 broadly simulates the same features observed in the NCEP reanalysis fields over Southern Africa, although MM5 produces more moisture than NCEP. The model results further indicate that more moisture is advected over the subcontinent from the South West Indian Ocean during the positive phase than during the negative phase of the SST feature. This is consistent with observed rainfall over the region during these events.

3.6 Evaluating appropriate physical schemes in MM5

This phase of the project is concerned primarily with understanding the causes of MM5 biases and the uncertainty inherent in the model due to different representations of the atmospheric physical processes. Three sources of observational data are used to identify biases in precipitation and surface temperature and relate these biases to the representation of key physical processes in the diurnal cycle. It is demonstrated that seasonal biases are an aggregate of biases on shorter timescales and although there are a wide range of MM5 configurations, the diurnal cycle offers a methodology to choose and improve which configurations are used.

The MM5 RCM contains several options for selecting how the model represents different atmospheric processes, e.g. the planetary boundary layer (PBL) and cumulus convection. This allows for many different model configurations and the appropriate choice for simulating the local climate is not obvious. We therefore tested these model configurations and compared the simulation of both a wet and dry season with the observed climate. In effect we are choosing a model configuration that best downscales the large-scale atmosphere.

3.6.1 Number of raindays

Figure 21 demonstrates the number of raindays simulated for each model configuration and for both the wet 1988/89 and dry 1991/92 season. On the right of each panel is the CRU observed number of raindays for comparison. It can be seen that the number of simulated raindays is dependent on the choice of cumulus convection scheme with the Kain-Fritsch schemes simulating too many raindays (20-30 extra per season) and the Betts-Miller scheme simulating too few raindays (10-15 less per season). These biases in number of raindays also reflected the biases observed in the seasonal mean surface temperatures, except for the KF2 convection + ETA PBL combination whose surface temperatures where closer to observed; the reason for this being its incorrect simulation of peak rainfall in the early morning which decreased the surface temperature through increased latent heat fluxes, offsetting the higher than observed incident shortwave flux due to the ETA PBL (see below).

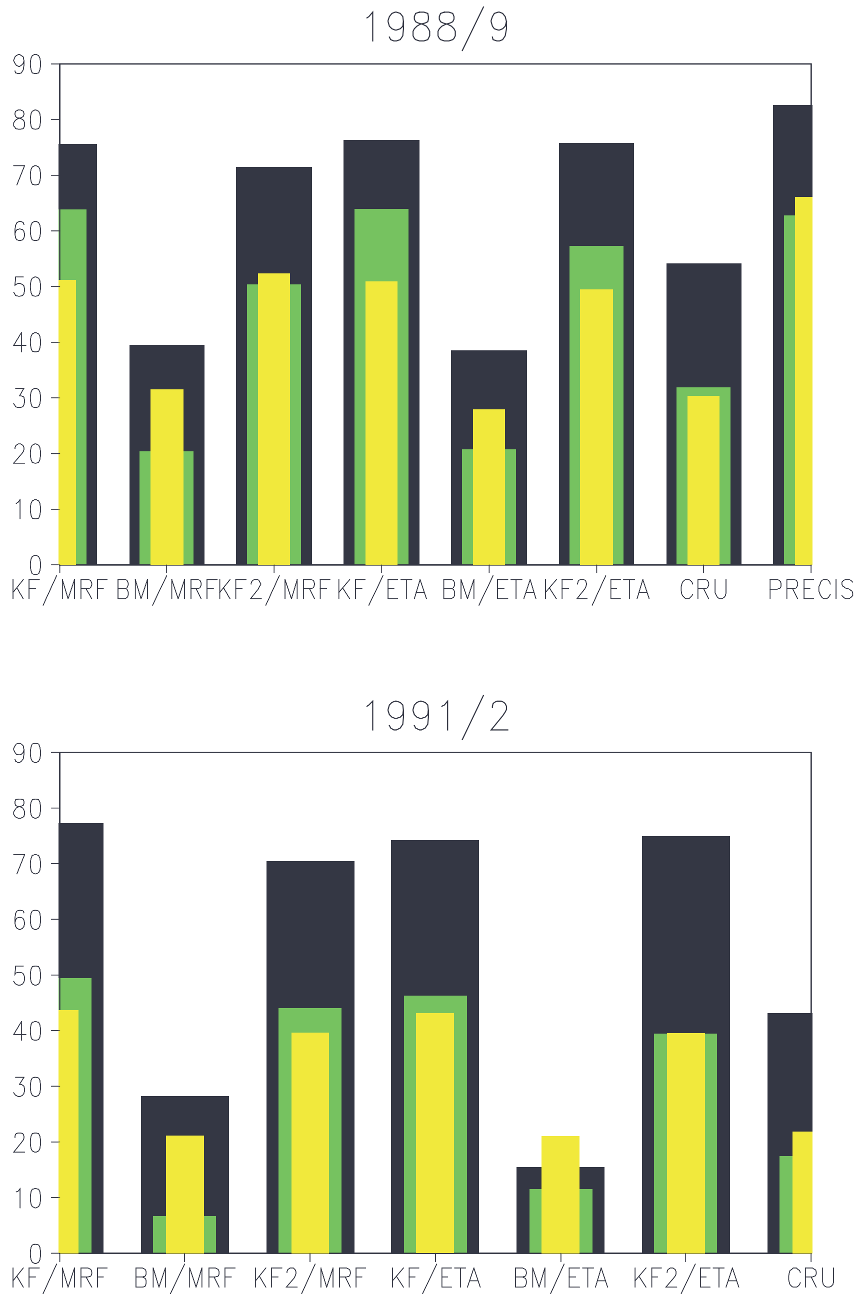


Figure 21: Number of MM5, CRU and PRECIS rain days (>0.1mm/day) for the 1988/89 and 1991/92 seasons. Tropics 17º-33ºE, 12º-17ºS (black), south-west 17º-25ºE, 20º-30ºS (green) and south-east 25º-33ºE, 20º-30ºS (yellow).

For the 1988/89 wet season it can be seen that the PRECIS model simulates too many raindays over each region and similar findings were noted for the dry 1991/92 season (not shown).

3.6.2 The diurnal cycle

Figure 22 demonstrates the diurnal cycles of rainfall, incident SW flux at the surface and integrated tropospheric cloud liquid water for 2 cumulus/Planetary Boundary Layer (PBL) combinations: BM/MRF[1] and KF/ETA[2]. These 2 combinations exemplify differences noted from comparing all 6 combinations of cumulus convection scheme and PBL; the choice of convection scheme dictates the simulated diurnal cycle of rainfall whereas the choice of PBL dictates the simulated diurnal cycle of incident SW. Comparing both combinations with the observations in Figure 22 indicates that the MRF PBL simulates a more realistic diurnal cycle of SW as has been noted for the arid regions of the south-western US (Bright and Mullen, 2002). This is attributed to the non-local formulation of the PBL, which entrains more air at the top of the PBL leading to increased cloud cover. Similarly the Betts-Miller convection scheme simulates a more realistic diurnal cycle of rainfall which peaks in the afternoon and early evening. This is confirmed by both the satellite data shown in Figure 22 and present weather reports (Dai, 2001). It is also noticeable from Figure 22 that the diurnal simulation of cloud liquid water varies between the two MM5 configurations: KF/ETA simulates peak CLW during the morning whereas BM/MRF simulates peak CLW during the afternoon. These differences can be seen in the 'skewness' of the simulated SW cycle: the BM/MRF combination more correctly simulates the peak during the morning.

Figure 10 also shows the diurnal cycle of the PRECIS RCM for the same season. In this diurnal cycle rainfall is mostly concentrated in the morning and this can be expected to lower the surface temperature through increased latent heat fluxes. However it's simulation of incident shortwave is more accurate than MM5, though at a coarser temporal resolution. Overall the PRECIS model appears to rain too weakly and too frequently over southern Africa.

The above experiments highlight the need to account for subseasonal biases when using MM5 to infer physical cause and effect on rainfall variability. The simulated atmosphere in MM5 is optically too thin but reduction in this and the other noted biases may be achieved with changes (appropriate for the local climate) to the empirical thresholds used in the convection schemes. This should be a goal of future model assessments and would reduce uncertainty in modelling and understanding local controls of climate.

Above all, these results indicate the imperative that a model be appropriately assessed; the consideration of seasonal means is not enough to ensure the simulation results are right for the right reason. This is a complicated and time consuming process, yet essential if the model simulations are to have credibility, and unfortunately all too often this is an activity poorly addressed. Finally, it can be recommended that the use of the diurnal cycle is an excellent diagnostic to evaluate simulation realism.

[1] MRF: the scheme used in the NCEP Medium Range Forecast Model
[2] ETA: the scheme used in the NCEP Eta regional forecast model

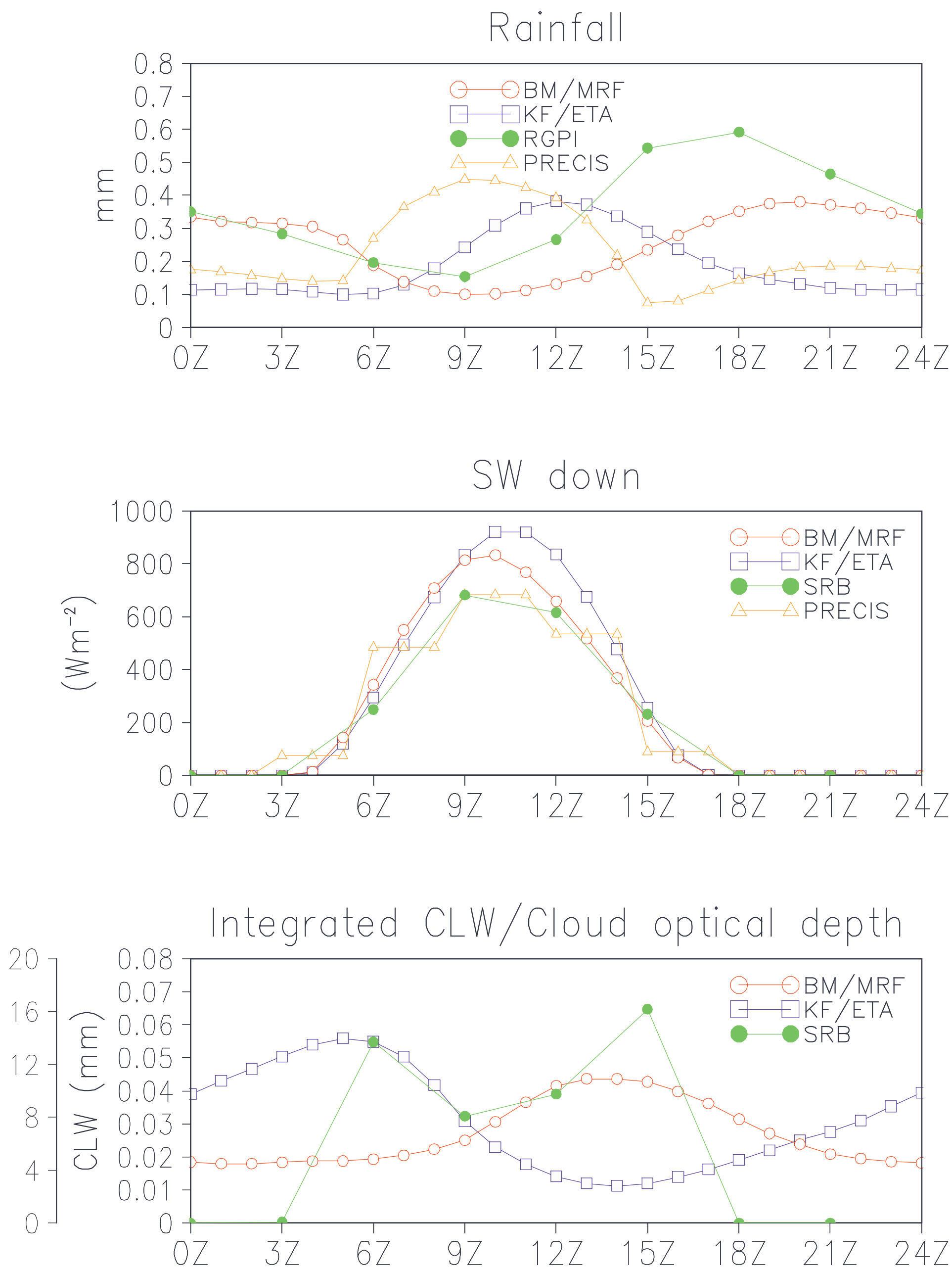


Figure 22: The diurnal cycle of rainfall (top panel), SW flux (middle panel) and integrated CLW/cloud optical depth (bottom panel) for the 1988/89 season. Observed datasets are filled circles, KF/ETA blue squares, BM/MRF red circles, PRECIS orange triangles. Data are averaged over the southern African region (17-12S, 17-33E).

3.7 Increased vertical resolution in the MM5 model

The PSU MM5 regional model uses a sigma vertical coordinate scheme to give a finite number of vertical levels on which calculations are performed. Sigma levels range from the lowest level, which follows the topographic surface in the model to the highest level, which is defined as the top of atmosphere pressure. This pressure is usually 10 hPa. Other levels are defined at various ratios between the surface pressure and the top of atmosphere pressure according to the equation:

$$P = sigma*(psfc-ptop) + ptop$$

The advantage of this scheme is that the model levels follow the model topography for lower layers while approximating pressure levels at higher layers, resulting in the fact that a model level can never intersect the model topography, thereby simplifying the model formulation. The main disadvantage is that advection in layers that are geometrically inclined is numerically complicated and must be corrected for.

The MM5 model allows different vertical level structures to be predefined according to the requirements of the simulation. Both the top of atmosphere pressure and the number and position of sigma levels can be specified. The standard model configuration included 23 levels with a top of atmosphere pressure of 10hPa. This configuration has been used extensively by many researchers around the world.

The motivation for increasing the vertical resolution of the model is that much of the moisture transport dynamics of the subcontinent involves transport of moisture over steep and significantly high topography. The most obvious example of this is the eastern escarpment of the subcontinent. It was also observed that the vertical structure of moisture in the atmosphere is often strongly structured and improving the number of layers in the model would help the model better resolve this vertical structure. This is particularly important for the lower atmospheric boundary layer where higher vertical velocities and mixing processes occur. The previous section discussed the different boundary layer parameterisation schemes and identified the boundary layer as a very important aspect of the regional model performance.

3.7.1 Implementation

Three model integrations were run. A control model was run using the standard 23 levels. The second model was configured with 40 levels while the third was configured with 50 levels. For the 50 level model a new sigma level was placed between every original sigma level except for the first three levels where an extra two levels were placed between each original sigma level. It is commonly agreed that model levels need to be more concentrated near the surface because of the stronger and more complex vertical motion in this part of the atmospheric column. The 40-level model used the same levels as the 50-level model but removed some extra levels at the higher model layers. The reason for this was pure pragmatism – to assess the question of computational efficiency. Model integration times do increase with increased vertical resolution though not as exponentially as with increases in horizontal resolution. It was hoped that the 40-level model would perform as well as the 50-level model while saving some model integration time.

3.7.2 Summary of model response to increased vertical resolution

The analysis concentrated on the vertical structure of moisture in the modeled atmosphere. This analysis clearly shows that over the eastern escarpment region there is greater vertical movement of moisture. While it is difficult to compare this with any observations because of the lack of observed vertical moisture profiles it is clear that increasing the vertical resolution of the model changes the simulated vertical moisture structure. While these changes translate into more realistic spatial patterns of precipitation, further work is needed to assess the degree of improved realism. This initial work, however, serves to highlight the need for appropriate configuration of the model for the complexities of the southern Africa domain.

3.8 Multiple nest, high resolution climate modelling

Mass and Kuo (1998) describe the benefits of regional climate modelling to improve understanding of weather systems and phenomena through high temporal and spatial resolution modelling for operational and experimental purposes. Experimenting with the model physics can optimize numerical modelling for a unique, localized region. In this light there are a broad range of spatial scales over which RCMs have been applied, including even global scale climate modelling (Dudhia and Bresch, 2002), along with modelling of specific atmospheric processes (e.g. Doyle, 1995; Lynch et al., 1997; Gauchon et al., 2001; Wang, 2001; Zhang et al., 2003;), high resolution regional climate modelling (e.g. Christensen et al., 1998; Hisashi et al., 1999) and the simulation of severe storms and flooding (e.g. Spencer and Strensrud, 1988; Li et al., 2003). Operationally, RCMs are being used for real time simulations at high resolution by various institutions; for example operational forecasts of regional weather (Horel and Gibson, 1994; Mass and Kuo, 1998), forest fires (Smallcomb 2001) and air pollution (Fast et al., 1995; Sistla et al., 2001).

Presented here are the results of studies in which MM5, capable of very high resolution climate modelling, was used to examine precipitation and wind flows in a topographically complex region. This phase of the project seeks to build capacity in multiple nested models addressing very high resolution tasks, and serves as a pre-cursor to future work focused on operational extreme event forecasting and analysis, as well as the use of RCMs for high resolution interpolation of weather station data in complex terrain (e.g. the Western Cape).

3.8.1 Methodological overview

The regional climate model used in these studies is again the MM5 RCM, demonstrating the versatility of this model framework; offering a common tool for a broad range of applications. In the context of high resolution modelling MM5-based studies include:

a. Modelling of severe storms and flooding (e.g. Spencer and Stensrud, 1998; Colle and Mass, 2000a)
b. Simulation and study of convective processes (e.g. Warner and Hsu, 2000; Zhang et al. 2003)
c. High resolution modelling of wind flow (e.g. Colle and Mass, 2000b; Feng and Chen, 2001; Chen and Feng, 2001).
d. Coupling of MM5 with other models such as an orographic precipitation model (Kuligowski and Barros, 1999), a sea-ice model (Wei et al., 2003) and hydrological model (Chen and Dudhia, 2001a,b).
e. Examination of the interaction of synoptic and mesoscale processes with topography (e.g. Chien and Mass, 1997; Chien et al., 1997; Colle et al., 1999b, Faccani et al., 2003; Roebber and Gyakum, 2003).

As topographic features in a given region establish the circulatory patterns of air masses from the synoptic scale down to the meso- and micro-scale, these features need to be accounted for in a RCM simulation. Thus, topography with a resolution such that orographic features are not smoothed away is necessary. The simulation domain would also have to be large enough to include all the terrain characteristics that are believed to participate in the circulation of the air masses, and these can often be far away from the study area. However, modelling a large enough domain at a high enough resolution to account for such orographic features makes it computationally impractical.

Nesting techniques attempt to solve this problem through increasing spatial resolution only in the domains where small-scale phenomena might occur and are relevant for the reproduction of all the forcing mechanisms in the study area. At the same time, outer domain(s) are also included at a coarser resolution, to ensure the introduction of larger scale synoptic forcings into the inner domain.

The non-hydrostatic, multiple nesting capabilities of the MM5 facilitates very high resolution climate modelling with a capacity to perform multiple nested runs of up to nine domains running at the same time. Each nest domain is completely embedded in a "mother domain" and is initialized with a progressively higher-resolution forcing data and topography. The interaction between the domains can be carried out through a one-way or two-way nesting technique. In the former, data from the outer domain(s) force the dynamics in the nested domain(s) at the nests boundary; using the latter technique, forcing occurs at the boundary of the nest as in the one-way technique, but there is also data feedback to the coarser domain(s) from the nest(s).

The studies presented below have been undertaken over the greater Cape Town region in order to model, understand and potentially forecast the meso and micro-scale properties of severe winter storms, which annually render thousands of people homeless, and cause millions of rands worth of flood and other damage. The results presented in this report describe the simulation of the passage of a series of mid-lattitude storms in August of 2001 and the simulation of a so-called “tornado” event in Manenberg in October 2002.

3.8.2 Simulating the passage of a series of cold fronts

During the winter of 2001, areas around the Cape Peninsula experienced severe weather and exceptionally high rainfall. Cape Town international airport reported well-above-average rainfall for August of 97mm, well above the climatology of 77mm (up to twice this or more in the mountain regions). A large portion of the City of Cape Town was declared a disaster area by the President of South Africa. The Cape Town City Council estimated 31 000 people to have been affected by the storms, including 8 000 homesteads. The total financial cost of these storms, including humanitarian aid (feeding, bedding and other immediate needs) and provision of basic household necessities (to re-establish homesteads), was estimated at R12 169 000. An improved understanding of the dynamics of the event, and the ability to simulate and forecast such events would greatly facilitate an improved preparedness of disaster management units in the region. Additionally, other sectors such as water management, aviation, ground transportation, electrical networks, construction, etc., for which knowledge of severe precipitation events would have important economic consequences, would gain from an improved precipitation forecast.

The MM5 simulation was run from 21-29 August 2001, which captured the passage of two severe cold fronts. Four domains were used with grid sizes of 27 km, 9 km, 3 km and 1 km using United States Geological Survey terrain and land use data of 19 km, 9 km, 4 km and 1 km respectively. The domains were chosen to capture synoptic scale forcing in the larger domain and interactions of approaching weather systems with the peninsula and its features in the smaller domains. Fifty vertical levels were used. The model was forced with twelve-hourly MRF global reanalysis data (1° horizontal resolution) from the USA National Center for Environmental Prediction (NCEP).

Precipitation processes were simulated using the Grell (1993) convective parameterization (there was no convective parameterization used for the inner three grids, rather at these scales the convective processes are resolved explicitly) and an explicit moisture scheme that included prognostic equations for cloud water, rain water, ice, and supercooled water (Reisner, 1998). The PBL was parameterised with the high resolution, multi-layer Blackadar scheme (Blackadar, 1979; Zhang and Anthes, 1982) and the radiation scheme was one in which longwave and shortwave radiation interact with the clear atmosphere, cloud, precipitation, and the ground (Dudhia, 1989).

3.8.3 Wind fields

Synoptic scale wind flow, such as the passage of cold fronts and ridging high pressures, is captured well in the lower resolution domains. As grid resolution increases from the synoptic scale to the meso- and micro-scale, surface wind characteristics become more defined as the effect of the enhanced topography (in the deeper nests) on wind flow becomes evident. Surface features such as deflection and splitting of wind streams, zones of divergence and convergence, increased wind velocities, and well defined land and sea breeze circulations have been identified (see Figure 23-28). The influence of the orography in the vertical was also modelled (using 50 levels in the vertical). During a westerly wind flow, a wave structure was set up in the lee of the peninsula, dissipating in amplitude towards the east.

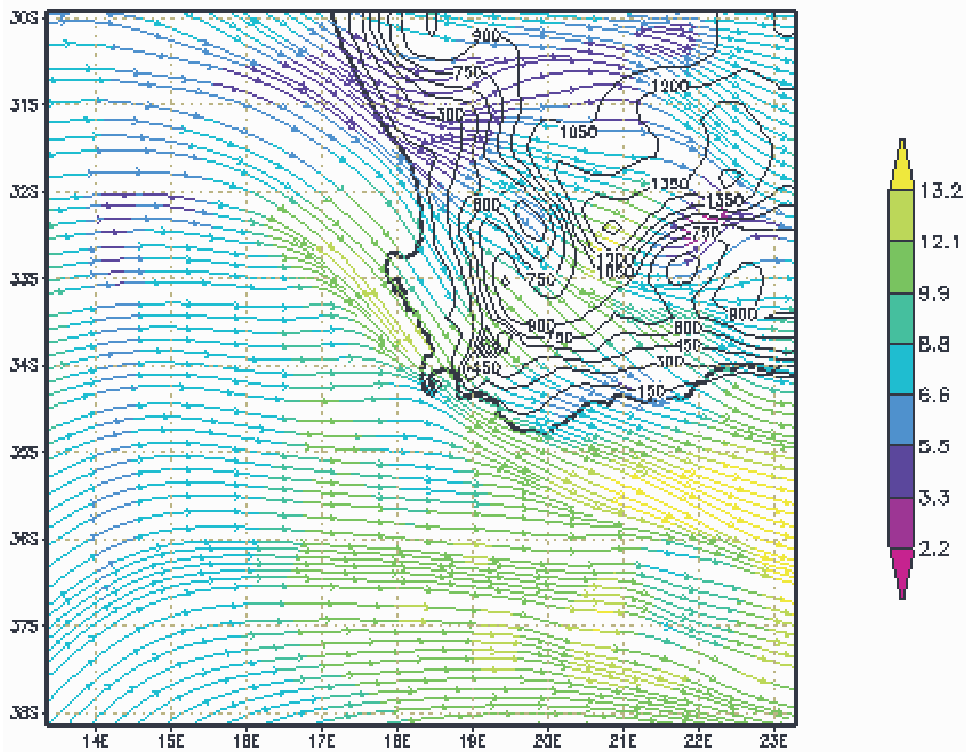


Figure 23: Synoptic surface wind fields at 20h00 on 23 August showing the passage of a cold front over the Cape Peninsula. Streamlines are shaded by velocity with the key bar in $m.s^{-1}$.

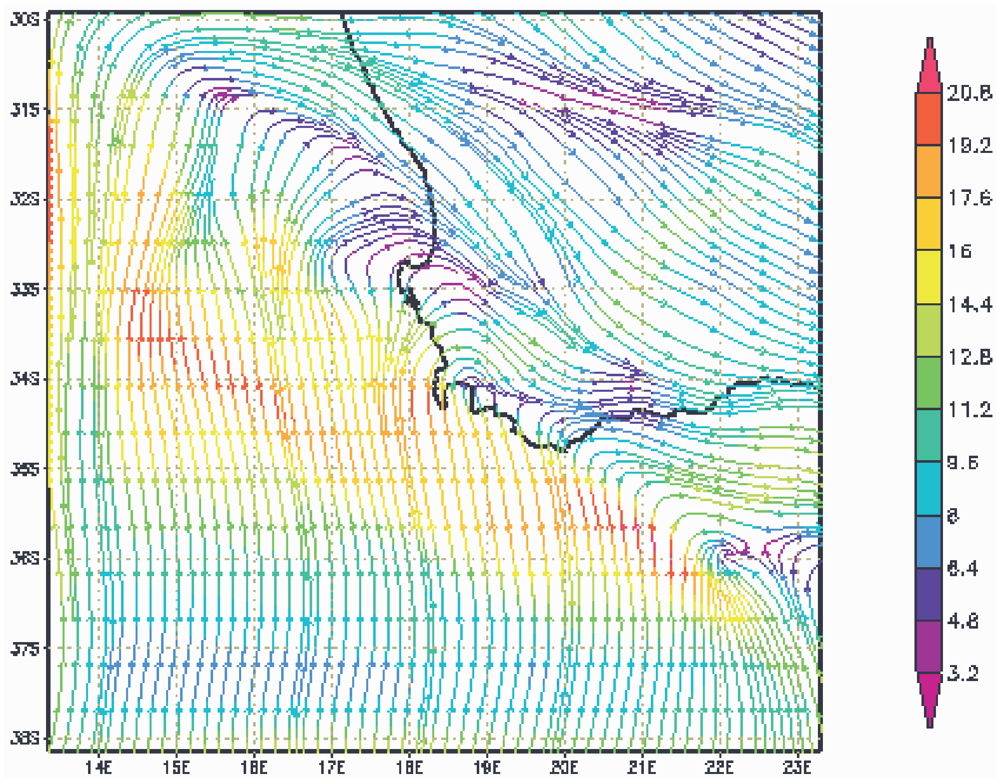


Figure 24: Synoptic surface wind fields at 12h00 on 29 August showing southerly meriodinal flow following the passage of a cold front. Streamlines are shaded by velocity with the key bar in $m.s^{-1}$.

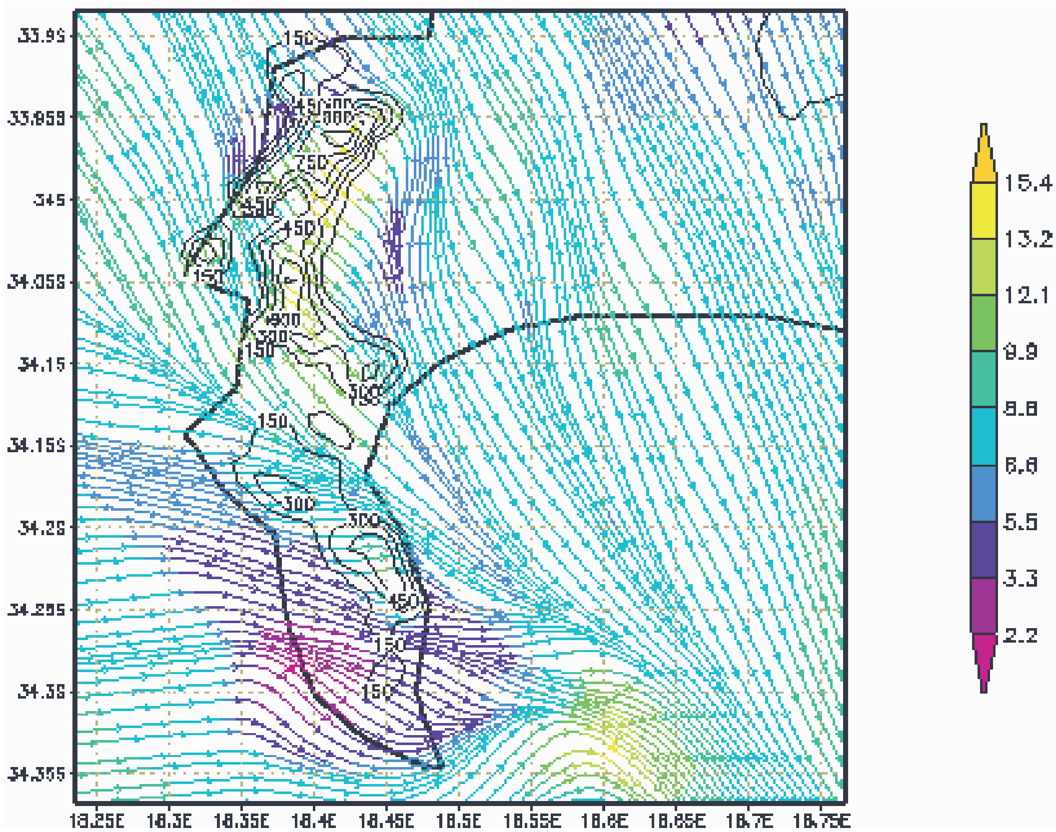


Figure 25: An orographically generated wave during NW'ly and W'ly flow on 23 August in the fourth domain. Streamlines are shaded by velocity with the key bar in m.s^{-1}.

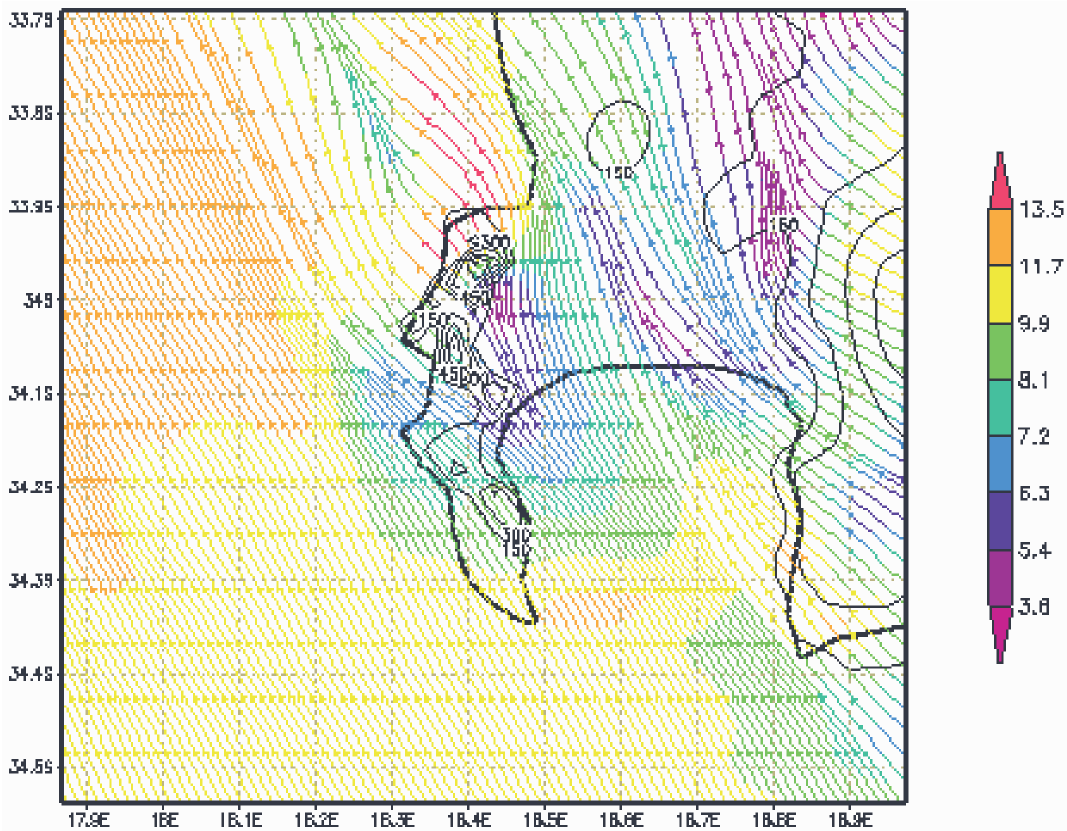


Figure 26: Patterns of divergence and convergence over the peninsula during SE'ly wind flow on the 29 August in the third domain. Streamlines are shaded by velocity with the key bar in $m.s^{-1}$.

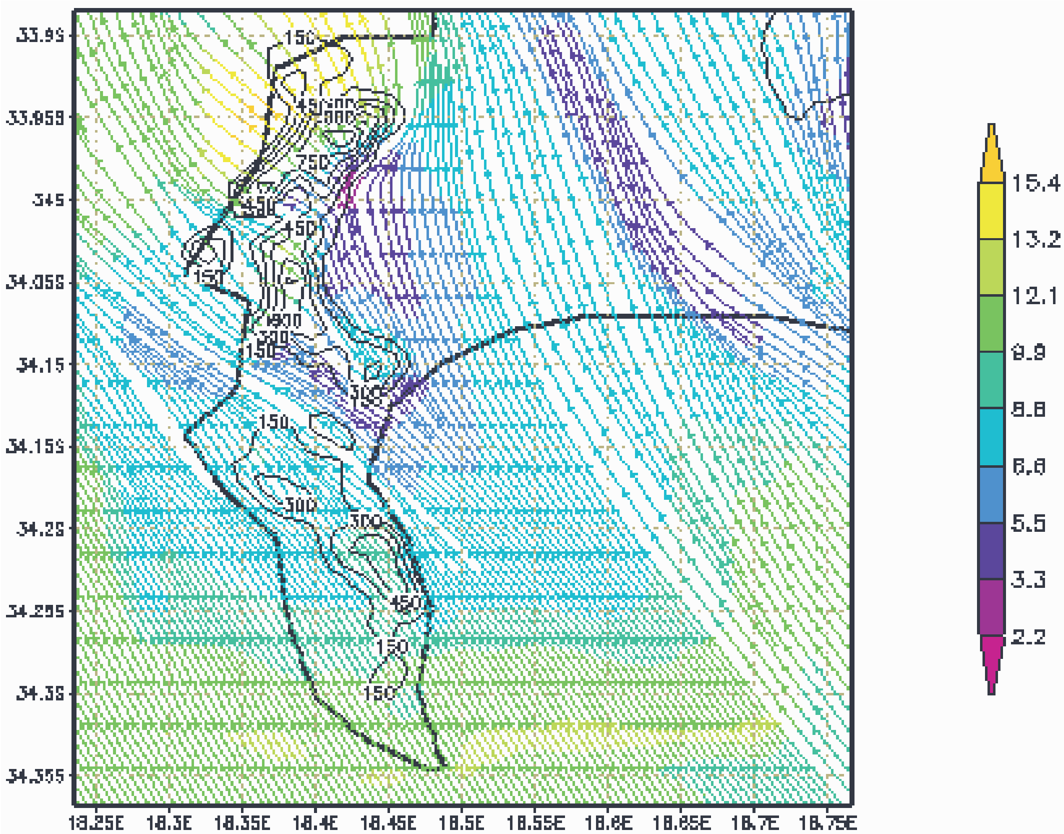


Figure 27: Streamlines showing evidence for split flow around Muizenberg during south easterly flow on the 29 August in Domain four. Streamlines are shaded by velocity with the key bar in m.s^{-1}.

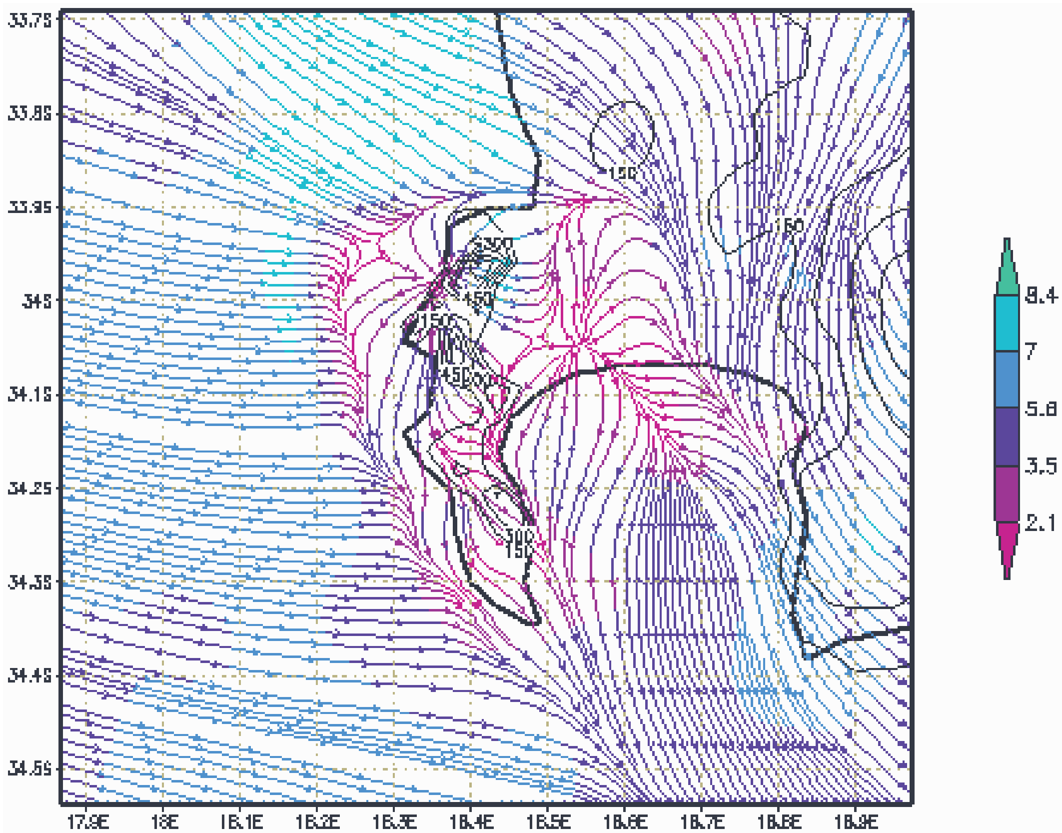


Figure 28: Surface wind deflection by topography during a WNW wind flow on the 25 August. Streamlines are shaded by velocity with the key bar in ms^{-1}.

Two-way nesting produces generally stronger winds and more complex flows than one-way nesting as a result of a better resolved topography over the nested regions.

Verification of simulated wind flows with observed data is not possible at such a high resolution (observed data is simply not available). However, members of the Cape Town yachting fraternity have anecdotally confirmed the simulated wind flows during certain wind regimes over False Bay and Table Bay (e.g. south easterlies or north westerlies).

3.8.4 Precipitation fields

Simulated precipitation increases becomes more spatially defined when moving from the first domain down through the nested domains (Figure 29-30). This is primarily as a result of the influence of the progressively higher resolution of topography of the nests allowing the model to more realistically simulate the effects of orographic forcing. Modelled precipitation data most resembles station data in the third domain using the one-way nesting technique as shown in Figure 30. It is thus adequate, for precipitation at least, to use a highest resolution grid size not finer than three kilometers, which has positive bearing on computational expense when running the model.

The use of the one-way versus two-way nesting procedures in this study indicates that this choice plays a significant role in determining the simulated precipitation. The two-way nesting technique greatly over-simulates precipitation (Figure 31, 32). This is as a result of the effect of an enhanced topography over the nest region of the mother domain. Here a positive feedback mechanism upwards and downwards between domains is set up: as (1) topography is enhanced in the nest area of the mother domain and (2) this domain receives precipitation data from the nested region which is biased towards higher precipitation. The positive feedback mechanism is set up which crosses all the domains. The resultant over-simulation of precipitation using the two-way nesting methodology is in this case study is of a high magnitude that renders the simulation unrealistic. The one-way nesting technique, although underestimating precipitation generally, renders more tenable results in this study while retaining realistic representation of the finer scales of the wind flow.

3.8.5 Simulation of a "Tornado" over Manenberg

At 18:30 on 2nd October 2002, a cold front made landfall over the Cape Town. At 20:15 reports of a tornado, which ripped of roofs and caused extensive damage to houses in Manenberg, were received. There was no meteorological evidence for a classic convective tornado and upon examination of the affected area, the feature was classified as a weak tornado of force F0 on the Fujita-Pearson scale. However, as the results below indicate, this attribution is probably incorrect, although in no way negating the very real damage incurred.

Simulation of this micro-scale feature required a five-domain run using 50 vertical levels. Grid sizes were 40.5 km, 9 km, 4.5 km, 1.5 km and 0.5 km with topographical resolutions of 19 km, 9 km, 4 km, 1 km and 1 km respectively.

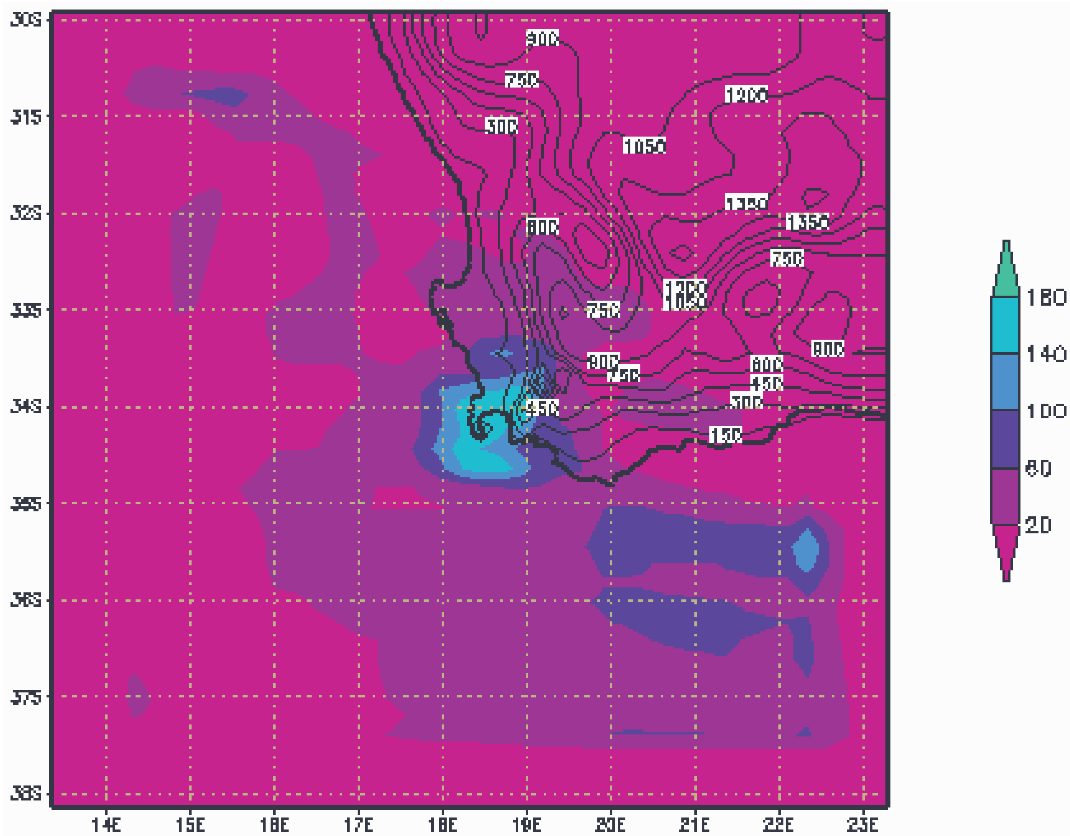


Figure 29: Accumulated nine day precipitation field for the two-way nested run in the first domain (mm).

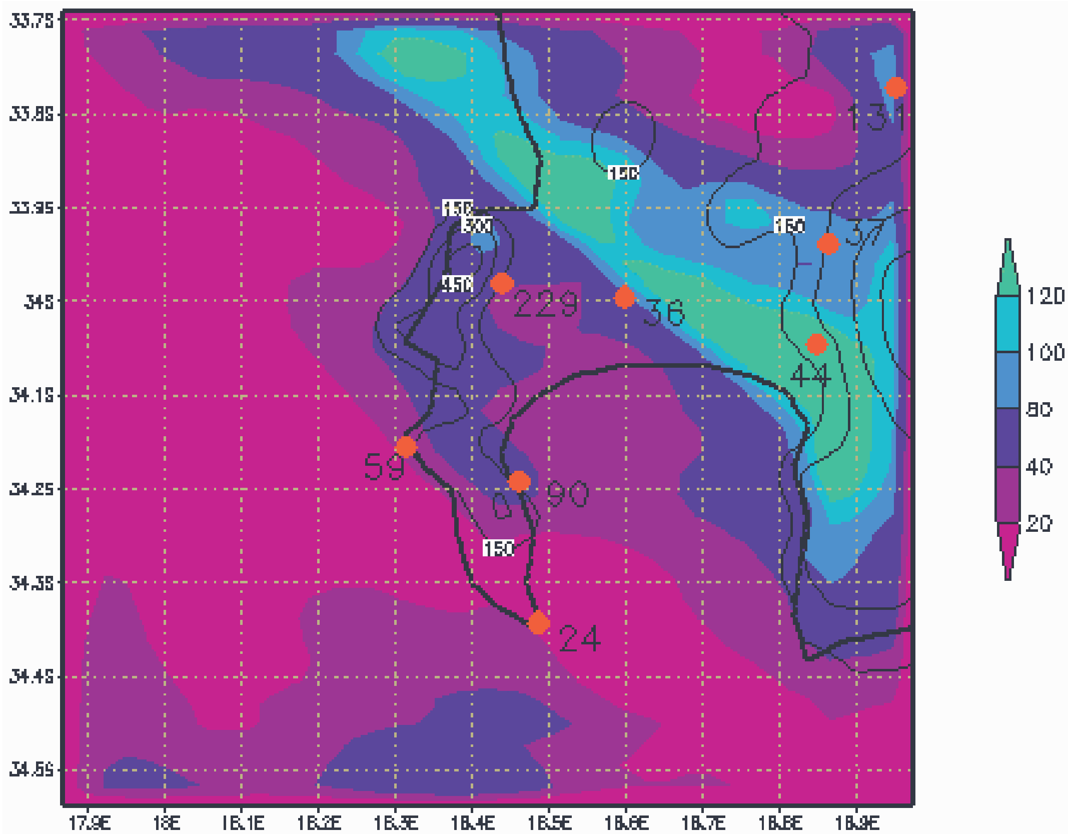


Figure 30: Accumulated nine day precipitation field for the one-way nested run in the fourth domain with recorded station data (mm).

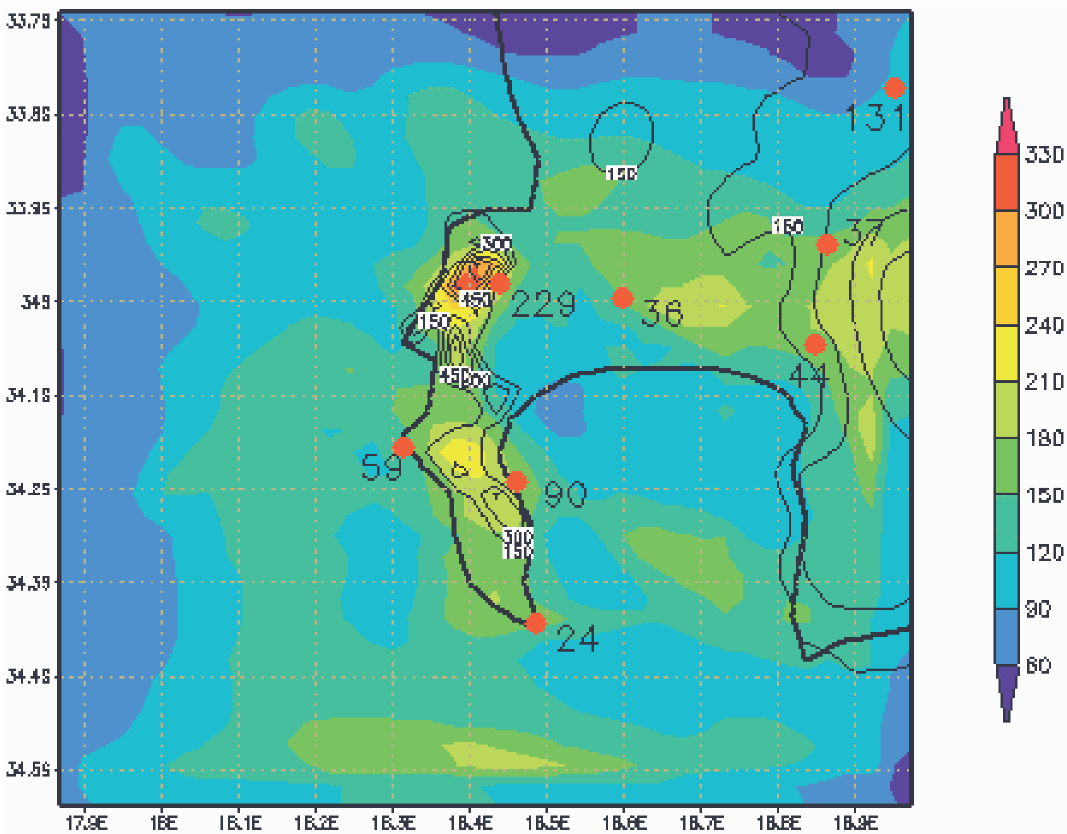


Figure 31: Accumulated nine day precipitation field for the two-way nested run in the third domain with recorded station data (mm).

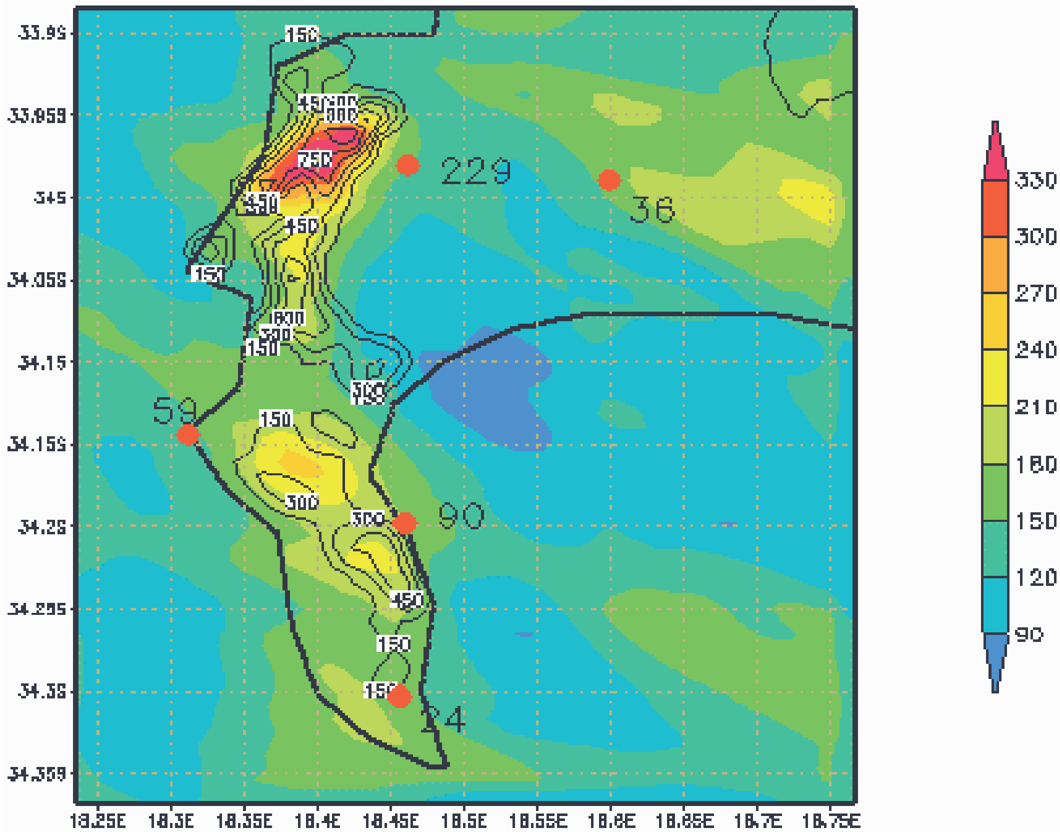


Figure 32: Accumulated nine day precipitation field for the two-way nested run in the third domain with recorded station data (mm).

The front as simulated made landfall between 18:00 and 18:30 (Figure 33). Wind flow changed from north-westerly to westerly until westerly flow dominated the region (Figure 34-36). During the westerly flow, a topographically induced wave can be seen in the lee of the peninsula at 20:00. This results as the westerly flow wraps around the face of Table Mountain and moves in a southerly direction It is in this wave that a small, strong vortex was established (Figure 37) and this turbulent feature then translates in a southerly direction. This feature was only evident for eleven minutes (between 20:08 to 20:19) before it dissipated. It was only clearly evident in the first two vertical levels of the model, indicating the feature was strongly constrained to near surface levels. A simulation using the one-way nesting procedure did not reproduce the feature, nor did similar simulations using four domains having a finest resolution of 1 km.

Thus, while further investigation is ongoing, the indications are that the “tornado” is a strong micro-vortex of short duration established by the interaction of the complex topography with the regional flow. Consequently, while the feature may not be predictable, it should be readily possibly to predict conditions conducive to the formation of similar events.

High resolution regional climate modelling thus facilitates an increased understanding of meso- and micro-scale climate circulation as it takes into account complex topographical features of the region. This study indicates that wind flows are realistically simulated at very high resolutions using the two-way nesting technique. Precipitation, however, is greatly over-simulated using this technique, and better results are obtained using the one-way technique, with no benefit being obtained at using very high grid resolutions.

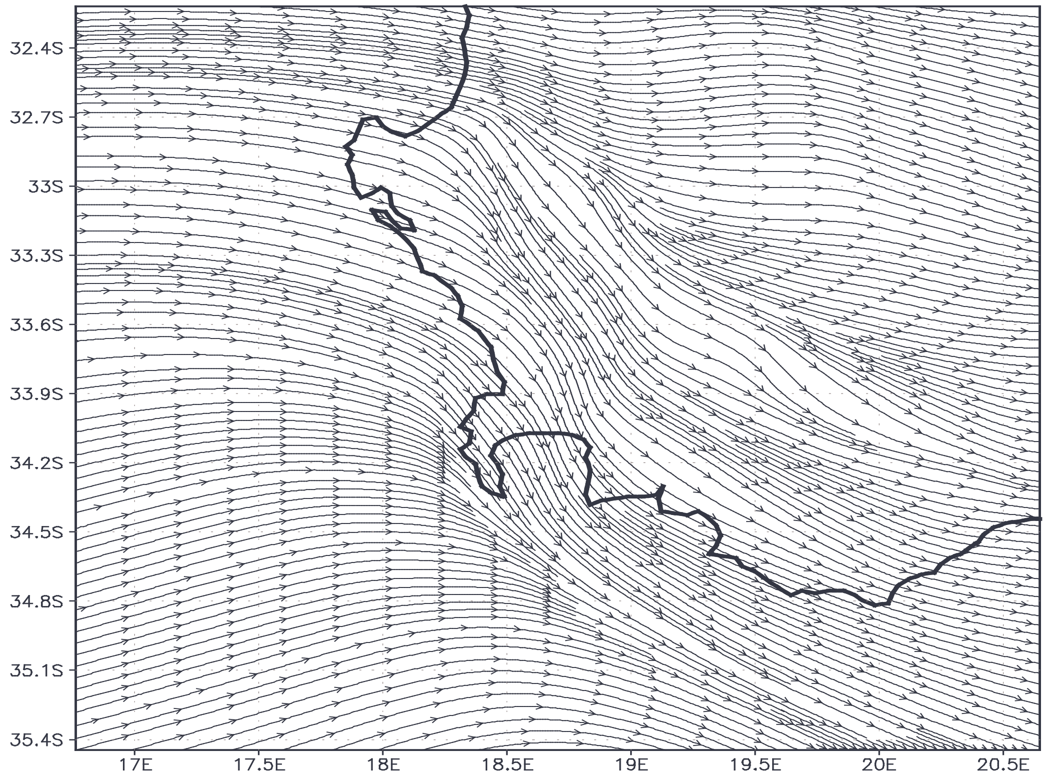


Figure 33: Synoptic scale wind regime change from north-westerly to westerly showing the position of the cold front as it makes landfall.

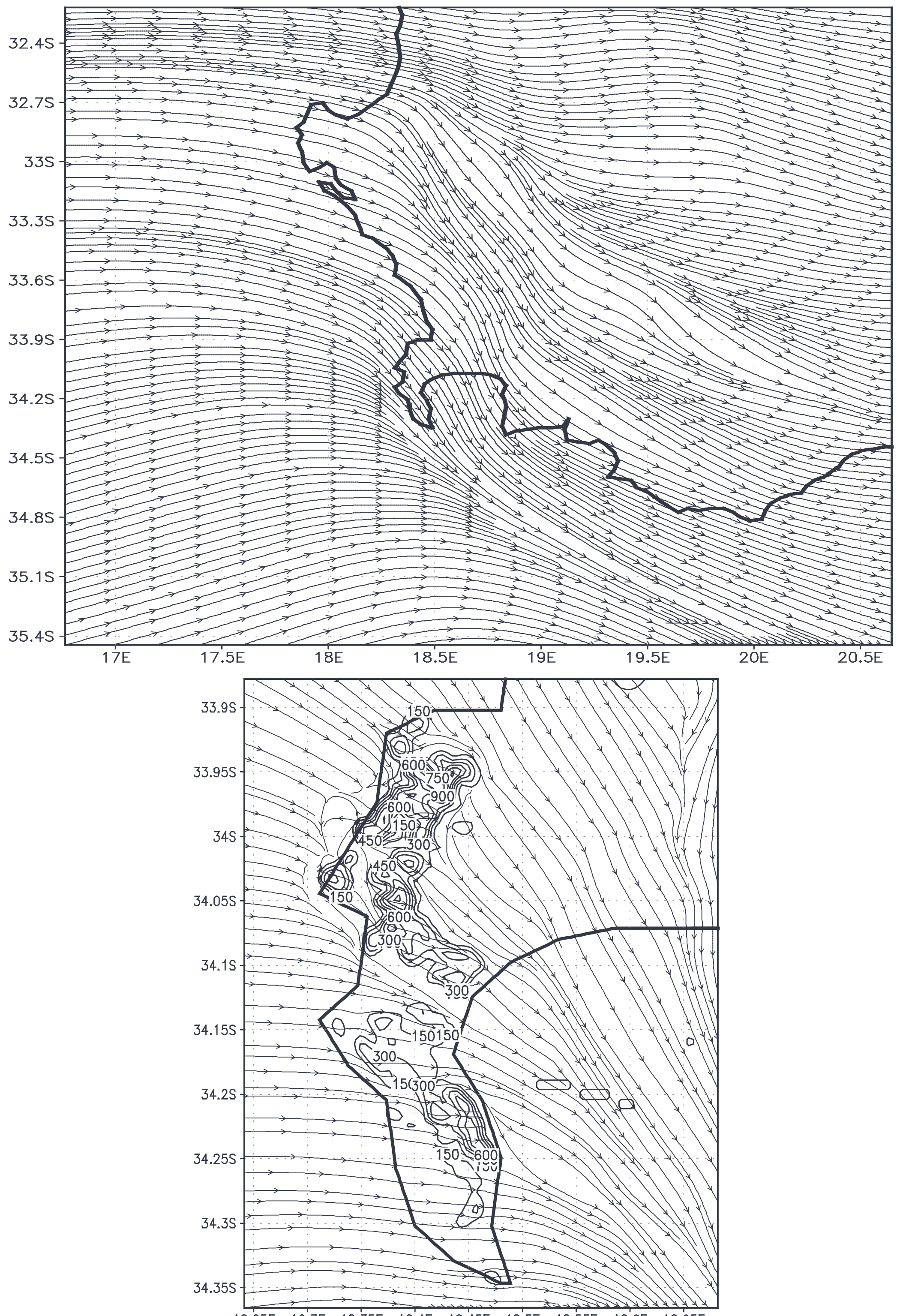


Figure 34: Synoptic and meso-scale wind flows at 19:00 showing a northerly flow at the northern peninsula and a westerly flow at the south.

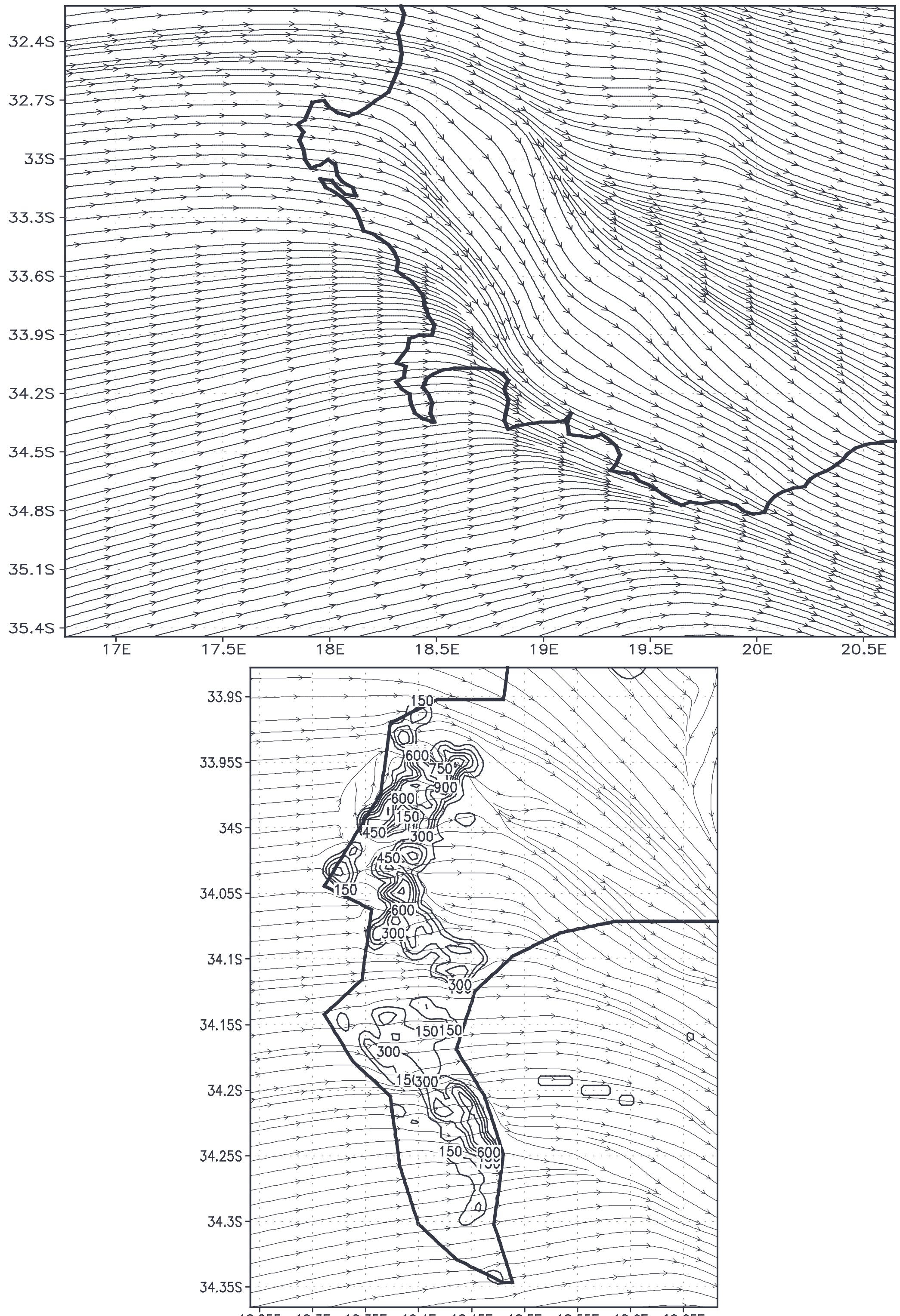


Figure 35: Synoptic and meso-scale wind flows at 19:30 as westerly flow begins to dominate the region. An area of topographically induced turbulence can be seen to be forming in the lee of the northern part of the peninsula.

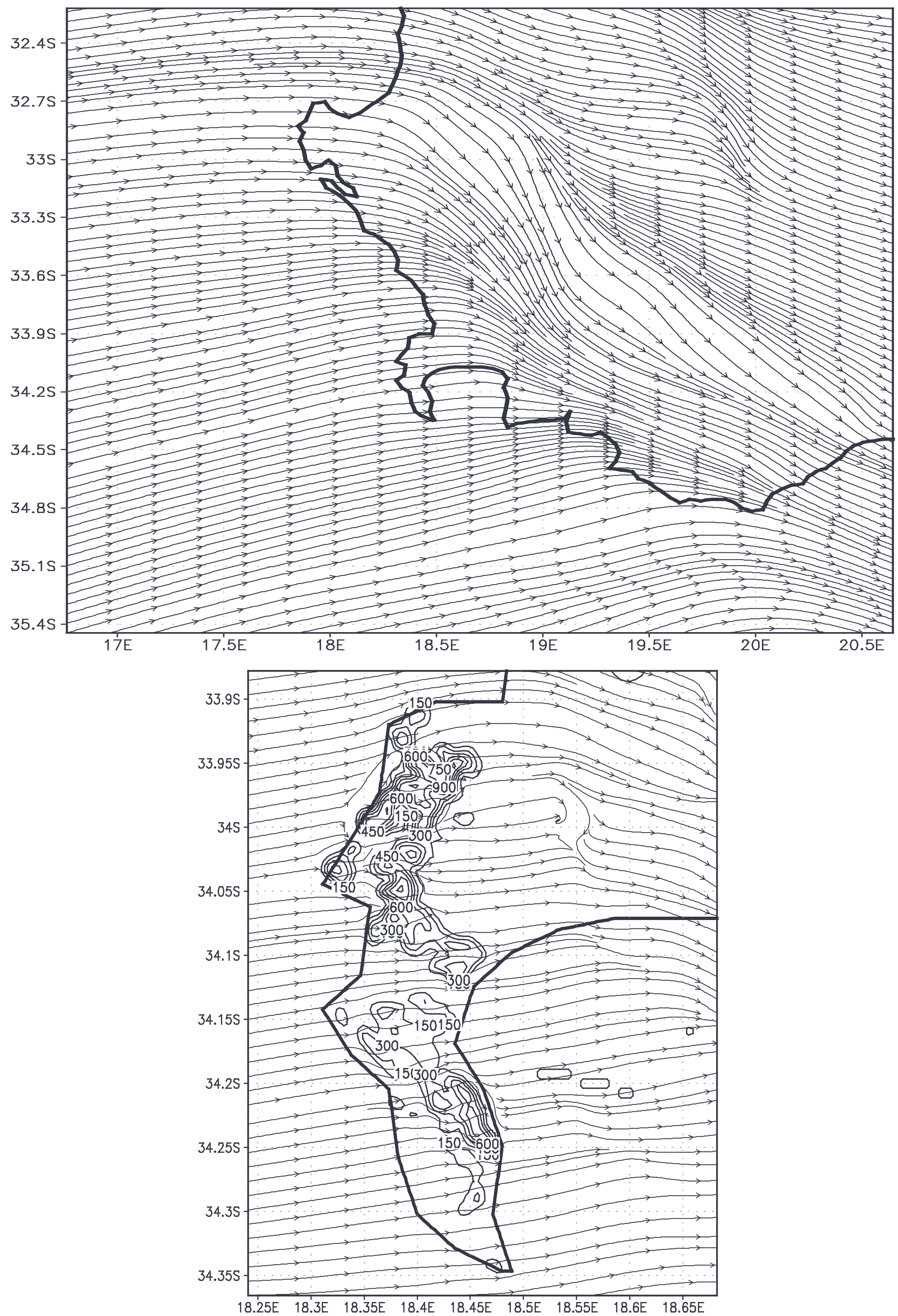


Figure 36: Wind flows at 20:00 showing westerly flow dominating the entire region and a wave set up in the lee of the northern peninsula in which the vortex formed. Isolines are topography in meters.

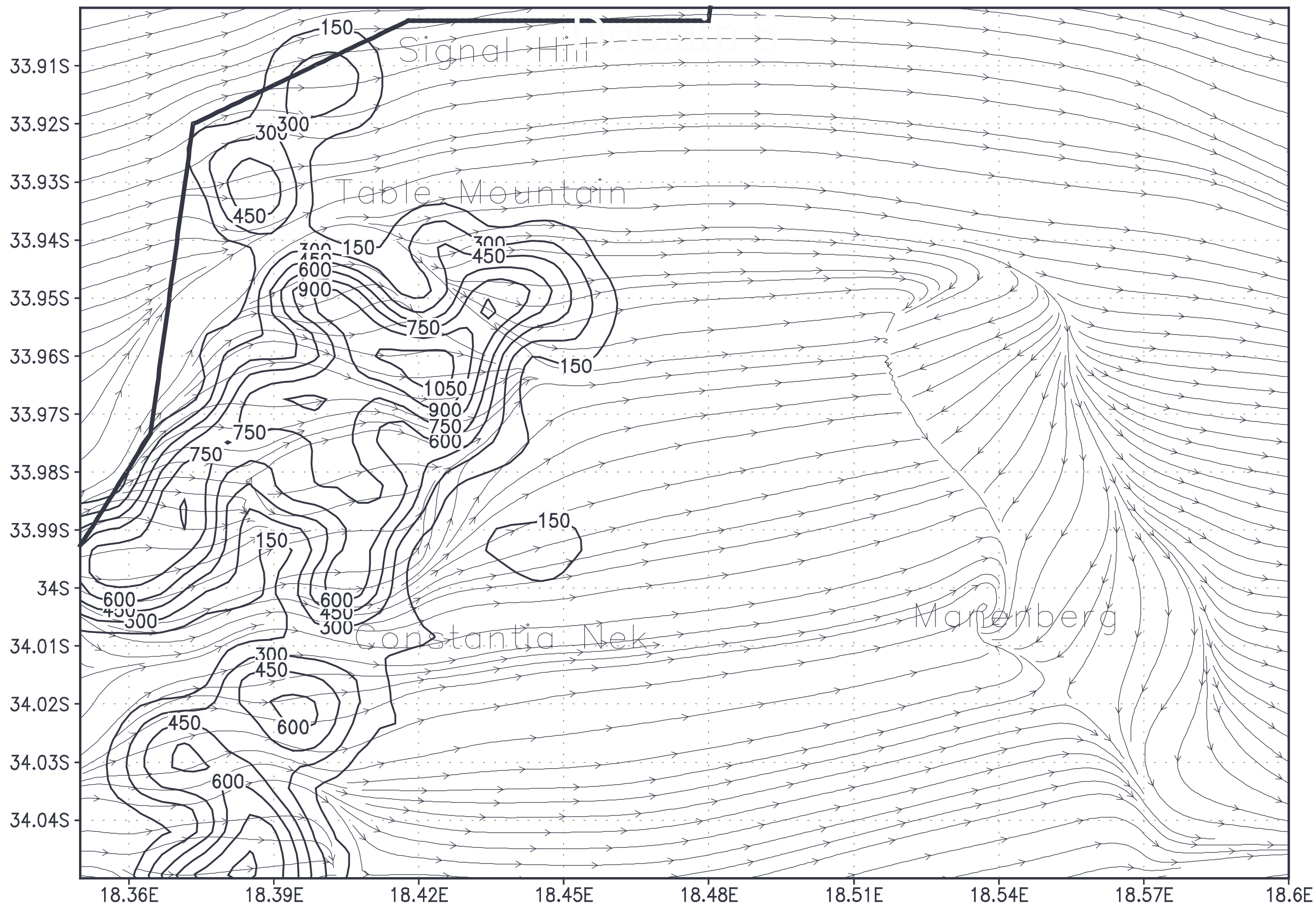


Figure 37: A zoomed image of the northern peninsula showing topographically altered westerly flow in the lee of the peninsula wrapping around the northern peninsula spawning a strong turbulent vortex near Manenberg.. Isolines are topography in meters.

4. Climate Change

The issue of climate change is, on the one hand, complex, while on the other is a topic about which we have great certainty. On the principles of basic physics it is clear that humankind is modifying the global climate system; the question is really that of firstly, to what degree, and secondly, what will the regional manifestation be. This latter question is of paramount importance as it is at the regional scale that adaptation and response strategies must be implemented.

4.1 RCM Climate downscaling

Regional climate models are a tool allowing for the dynamically downscaling of GCM-resolution fields to much higher spatial resolutions. However because of computation limitations most regional model downscaling experiments focus on time scales ranging from a few days to a few months. While these time scales are very useful for studying the dynamics of particular atmosphere events or the dynamics of the climate over a particular season they are limited in providing a picture of the long term dynamics of the climate system. In order to do this much longer integrations are needed. A secondary and very important benefit of such long integrations with the RCM is that of model verification. While a regional model might perform well in simulating a particular event or even a season, the question of how well it performs at a climate time scale is often not known. Useful insights into model biases, strengths and weaknesses under wide ranging atmospheric states can thus be obtained by long duration integrations.

An additional motivation for this kind of model integration is for the dynamical downscaling of future climate changed scenarios. GCMs are used to produce projections of future climate and different emission scenarios but these projections are at a very coarse scale and the local scale response and feedbacks are not resolved. Dynamical downscaling provides a tool whereby these local scale responses and feedbacks can be resolved and studied. However before regional models can be applied to this problem they need to be validated under current climate conditions. These integrations are therefore invaluable in evaluating and improving regional climate models and so enabling us to apply them to future climate downscaling with confidence.

4.1.1 Methodology

The MM5 model was again used for these integrations. The technical hurdles involved in performing decade length integrations with this model will not be described in detail but it suffices to say that CSAG is one of the first groups in the world to accomplish this and we are currently helping other groups in the UK and the US to perform similar integrations.

The period of 15 years was initially proposed as a suitable integration period as it seemed a good compromise between computational limits and climate statistical analysis. However in the initial run only ten years were integrated before an insurpassable technical problem occurred. Discussions with colleagues around the world resulted in changing future integration periods to 10 years – this is not an insurmountable problem, merely a pragmatic decision in light of the current project objectives. While this is quite a short period climatologically it was felt that this was more realistic given the computational limits.

The integration was started in January 1985 and run for a period of one year at a time. At the end of each year the model generates a save file which saves the complete state of all model variables. The model then terminates while new boundary conditions are generated for the next year of integration. The model is the restarted and initialized with the data from the save file thus providing seamless continuity between integration years. Model variables are written out at a 6 hourly time period providing four snapshots of the model state per simulated day.

The chosen domain of the model extends from the equator to 40ºS, and from 5ºE to about 45ºE, thus covering the whole southern African subcontinent as well Madagascar. The inclusion of Madagascar was the result of a moisture trajectory study (Hewitson, 2004) suggesting that moisture transport into the subcontinent is strongly influenced by Madagascar. In addition Madagascar is potentially strongly influenced by climate change and the ability to apply the model to climate projection downscaling seemed worth the extra computational load involved in including it in the domain.

So far a preliminary ten year simulation has been completed and some analysis has been done. The results of this, which will be discussed below, as well as the extensive experimentation with different model configurations discussed earlier, suggested that second integration should be started. This integration is currently nearing completion and analysis will begin shortly.

4.1.2 Results

Previous regional modelling experiments by CSAG have concentrated mostly on South Africa. However collaboration with other African countries and research projects as well a growing awareness of the interactions between different parts of the African climate system suggest extending the modelling domain further North. A major consequence of this is that the elected model domain now includes tropical regions. Convective precipitation in the model is handled by parameterizations, for which many options are available. Whereas an earlier choice of parameterisation was based on performance only in the extra-tropical area of South Africa, the inclusion of the tropics and the insights obtained form the paramaeterization tests indicated a different parameterisation scheme package as optimal for climate simulations.

The following results are from the first integration. Changes to the model are currently being tested and these changes already show marked differences to the previous configuration. However the older results still give a valuable insight into the performance of the model over a long time integration. We will focus largely on the performance over South Africa.

Boundary layer temperature

The summer season boundary layer temperature fields show large scale similarities but there are some anomalies. Notably the regional model is simulating lower temperatures over the areas of high topography that extend up most the Eastern side of the subcontinent as well as Madagascar. This is spatial detail that the regional model is adding to the large scale driving fields at scales smaller than those of the boundary forcing data. However, two large areas show significant warm anomalies in the regional model. One area centered in Northern Botswana and extending into Namibia, Angola and Zambia, and another large area in the Democratic Republic of Congo. These differences do not appear to be topographically related.

The winter season results) are similar to those of summer, although there is a smaller cold bias over the high topography. The anomaly over Northern Botswana does not appear in winter but the anomaly over the DRC is still present. These anomalies are significant and require further investigation.

Boundary layer specific humidity

The summer season shows some significant large scale differences between the two models. The regional model shows Madagascar to be much drier though this is probably largely related to the topography. The greater part of the subcontinent away from the coast is significantly drier in the regional model. This may be a result of topography blocking of the flow of moisture from the East that is simulated in the regional model but not the reanalysis. Further analysis and comparison to observed data will be required to determine which model is more accurately simulating the moisture across the subcontinent.

The winter season shows much smaller differences in this variable. This is probably because the transport of moisture into the interior of the subcontinent is much reduced during winter so if the regional model is blocking this flow more than the global model it will not be so apparent in winter.

Comparison with observed precipitation

A comparison as above between the regional model and the data from the forcing large scale model is a useful exercise and can identify possible problems with the regional model integration. However a more useful comparison is to compare the output of the regional model with some observed quantity such as precipitation. This was done for only for South Africa owing to the limitations of the observed dataset available for this study. The first is a full year climatology comparison. The second and third are seasonal comparisons with a summer season climatology and a winter season climatology.

The results for the whole year comparison show that the regional model is skilful in simulating precipitation over the country. There are some differences, the most notable being the excessive precipitation the model produces over the steep Eastern topography of the country. As discussed above, this is probably partly a result of the inadequacies in the observed station network in this area, but also partly because of inaccuracies in the way the regional model handles the advection of moisture and vertical motion over steep topography.

Another marked difference is seen in the extension of the high rainfall belt around the South of Lesotho. The model produces a large tongue of rainfall extending from the South East coast into the interior that is not seen in the observed data. However the model does capture the coastal rainfall along the south coast which is largely topographically forced rainfall. The rainfall in the South Western corner of the country is largely produced by mid-latitude systems interacting with topography of the area. The model does capture this precipitation though not with sufficient magnitude.

Summer precipitation

In summer the differences over the Eastern escarpment are even more prominent because of the much higher rainfall in the area during summer. Most of the Eastern and Northern part of the country experiences summer rainfall so most of the anomalies in rainfall occur during the summer season.

Winter precipitation

In winter most of the country is almost dry. The significant rainfall occurs over the SW corner of the country. This rainfall is a result of the interaction of mid-latitude frontal systems with the high but narrow mountain range in this area. While the regional model does smear out the rainfall further inland than is seen in the observed, it is still impressive that it captures it as well as it does. The much smaller rainfall that extends along the South coast of the country is also captured well. The MM5 regional model, like most regional models, tend to produce to much trace rainfall and so struggles to actually produce zero rainfall. As a result most of the country is covered by a trace of rainfall that is not always present in the observed data.

Area averaged time series

Spatial climatology maps are useful in determining how well the model captures the observed distribution of rainfall. However, they are long term climatologies produced by averaging over ten years of data. An analysis of the temporal evolution of the model generated rainfall is also useful. However it is difficult to compare a single model grid point to a particular station or even a grid point from a station derived dataset. The model grid point represents the average rainfall across the whole model grid whereas the station data represents the rainfall at a number of stations in the area. Often a single station, or even a number of stations are not particularly representative of the area covered by a model grid box.

In order to minimise this effect monthly time series are generated by area averaging over several model grid points, both for the regional model and for the observed data. It must be noted that even this is prone to exaggeration of errors. If a precipitation system produces a particular pattern of precipitation, even if the regional model produces almost identical patterns, a slight difference in location can produce two quite different area averaged time series. However it still a reasonably good way of evaluating the temporal evolution of a model. Two monthly time series were produced. The first was a 2x2 degree box over the NE corner of the country. This is an area of summer rainfall but is not an area of particularly significant topography. The second was over the South Western part of the country. This is an area of winter rainfall and so should show quite a different temporal evolution.

North Eastern time series

This time series produced from the area averaged box over the NE of the country (Figure 38) shows that the regional model generated monthly precipitation values do not agree well with observed values. The regional model seldom agrees with the observed data as to which month is the wettest of the season. However, of interest is that whenever the observed data shows a peak in the middle of the winter season, the regional model does the same. Clearly the regional model is managing to capture the processes that produce this wet month in the middle of winter in a summer rainfall region.

Much of the precipitation in the region is convective and consists of large convective structures that go through rapid phases of birth, activity and decay. The exact location and track covered is fairly stochastic. So it is not particularly surprising that the two series are so different. It could largely just be the stochastic nature of the precipitation that causes the differences.

South Western time series

The time series produced from the South Western corner of the country shows similar characteristics to the other time series. The annual cycle of precipitation is not as structured as with the North Eastern time series. The precipitation is far more evenly distributed through the year though it is clearly a winter rainfall region. Once again the regional model generally fails to agree with observations as to which months are wet and which are dry. The large peaks in the observed time series are seldom matched in the regional model time series.

As already mentioned, the results of these analyses have prompted a new, reconfigured integration which is currently nearing completion. However much experience has been gained through the first integration and improvements to the model and better understanding of the models biases and problems as well as it's strengths have lead to greater confidence in the use of RCMs for studying the region's climate system as well as for downscaling large scale atmospheric fields to the local scale.

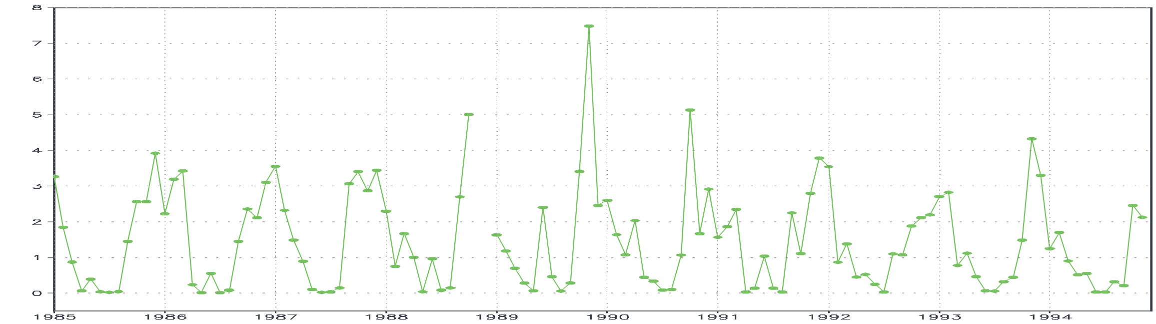
4.2 Complementary Climate Change experiments

It has already been mentioned that RCMs make a very useful tool in understanding the dynamics of the atmosphere. They are also very useful in climate change studies as they can be used to downscale the data from GCM simulations over a smaller domain.

As part of the AIACC[3] project, and explicitly building on the capacity generated through this WRC project, the University of Cape Town is involved in the downscaling of climate scenarios simulated by three different GCMs. This downscaled data will then be disseminated to be used by researchers in impact studies. The three GCMs involved are the HadAM3, the CSIRO and the ECHAM4 models.

Since the PRECIS model has been specifically designed to use the output from the Hadley Centre's other regional model, the HadAM3P, the model will be tested with the

[3] Assessments of Impacts and Adaptations to Climate Change: see http://www.aiaccproject.org/



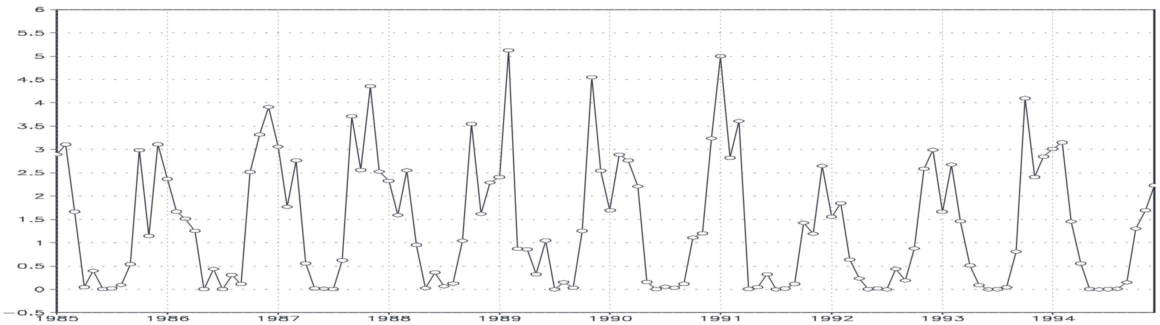


Figure 38: Monthly averaged precipitation (mm) for an area in the North East of South Africa. (Top panel: MM5, Lower panel: Observed)

A2 and B2 data from the HadAM3P. This will be done as soon as the initial testing of the PRECIS model over the southern African region has been completed. Modification to the PRECIS model is also expected in the near future so that the use of data from other GCM will be possible. This will allow the use of the other two model's data to be downscaled using PRECIS. The downscaling of the GCM data using MM5 is still ongoing, and the results form MM5 and PRECIS, along with empirical downscaled scenarios, will be available to user communities towards the end of 2004[4].

4.3. GCM Climate Change experiments

The principal tool for assessing global climate change is the coupled ocean-atmosphere GCM. The application of GCMs to the question of climate change has clearly shown that a) anthropogenic is a real and serious threat to global development and sustainability, and b) that it is possible to make clear statements of attribution with regard to past climate change. The most recent IPCC[5] Third Assessment Report (TAR[6], 2001) clearly shows how the climate trends of the past century cannot be explained without taking into account changes in greenhouse gas concentrations as a result of human activities. The TAR notes that it is likely[7] that most of the global warming in the past 50 years may be attributed to anthropogenic changes in greenhouse gas concentrations in the atmosphere. Given that societal dependency on fossil fuels will not change in the near future and greenhouse gas concentrations will continue to increase, that the climate system response has inherent delay to the forcing from green house gasses, and that the response will likely accelerate, it seems virtually certain that the climate system of the next 50-100 years will increasingly impact all sectors of society, and that in all probability we are already seeing the early evidence of these impacts.

Consequently, in order to appropriately respond through developing adaptation and management policy, it is imperative that a clear understanding be developed with regard to the regional manifestation of global climate change. Inherently such understanding is dependant on the GCM; the GCM provides the core understanding of the climate system response to the anthropogenic induced greenhouse gas forcing. However, GCM skill lies at the synoptic scale, not at the local scale where the understanding of the manifestation of climate change is most urgently required. Various downscaling procedures have been developed (in part through WRC support, see Hewitson, 1999). For the most part practical downscaling has to date been implemented through empirical techniques. New refined products building on past WRC supported developments, using empirical downscaling, are at present being distributed to end users in the water and botanical sectors. Within this project, however, the RCM-derived product, nested within the GCM, is still in developmental stages and is likely not of the same skill as empirical approaches.

However, there is still much that may be learned from the coarse resolution GCMs. Most particularly, whether the raw GCM product is directly used, or whether the GCM is used

[4] Some empirical downscaled scenarios are already available.
[5] Intergovernmental Panel on Climate Change
[6] See http://www.ipcc.ch for downloads of the TAR.
[7] "likely" is a term with specific statistical significance in IPCC language; in layman terms it would perhaps better be expressed as "very probable".

to drive downscaling, there is a critical need to assess the skill, error, and bias in the GCM. Such assessment needs to be undertaken very specifically, with the intended use of the GCM data clearly in mind. Historically, much of the GCM evaluation has been in simple terms; largely time-space averages. However, the climate system may readily respond through strong changes in daily weather events which, when amalgamated to some space-time average could readily show no significant change. Hence evaluation of the GCMs should be undertaken with the data at appropriate resolutions. Further, even once a GCM is evaluated, it must be recognized that one GCM alone offers only one possible climate system evolution; that there is an envelope of future possibilities is clear and consequently multiple GCMs should be assessed in any climate change study.

The following sections focus on procedures for appropriate evaluation of GCMs; this work being at the cutting edge of current approaches to this task. No recommendations to which GCM is "best" is made, nor is there any intention to undertake a relative ranking of GCMs. Rather the focus is to develop the appropriate framework for undertaking further studies with GCMs through both empirical and nested RCMs. In particular, the work within this project has directly supported the activities of the AIACC project across Africa, and also feeds into the current WRC project on Global Climate Change and Water Resources in Southern Africa[8].

4.4 GCM validation procedures

As noted above, model validation needs to be undertaken in terms of the intended application of the GCM data. In this project, given the intended application of the GCM for driving the RCM, it is essential that the GCM provide appropriate boundary forcing, as graphically shown in Figure 39. The assessment of the boundary fields in the GCM is complex; the GCM dates have no direct complement in the observed data set, and the fields of concern are the vertical faces that border the RCM domain.

To assess this requires assessing the statistics of the faces of the RCM boundary, at the temporal resolution used to drive the RCM. In terms of time-averaged variables this is a simple task. Figure 40, for example, shows the time-averaged boundaries of the RCM domain from the NCEP reanalysis data and from the ECHAM GCM simulation of present day climate. While there are differences it is arguable that the ECHAM GCM has a credible representation of reality. However, what is required is an assessment in terms of the 6-hourly fields used to drive the GCM.

To undertake this a Self Organizing Map (SOM) is employed. The SOM is an analysis tool that conceptually is simple; the SOM provides a means to categorize the 6-hourly data set to find archetypes – typical states that represent the continuum of possibilities found in the data. Full details of a SOM are not presented here (see Hewitson and Crane, 2002, for details), as it is enough to understand that the SOM represents states of the continuum. The actual data may then be mapped to these states allowing a frequency of occurrence to be determined for each state.

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[8] A 2-year WRC project undertaken jointly by the Universities of Natal, Witwatersrand, and Cape Town.

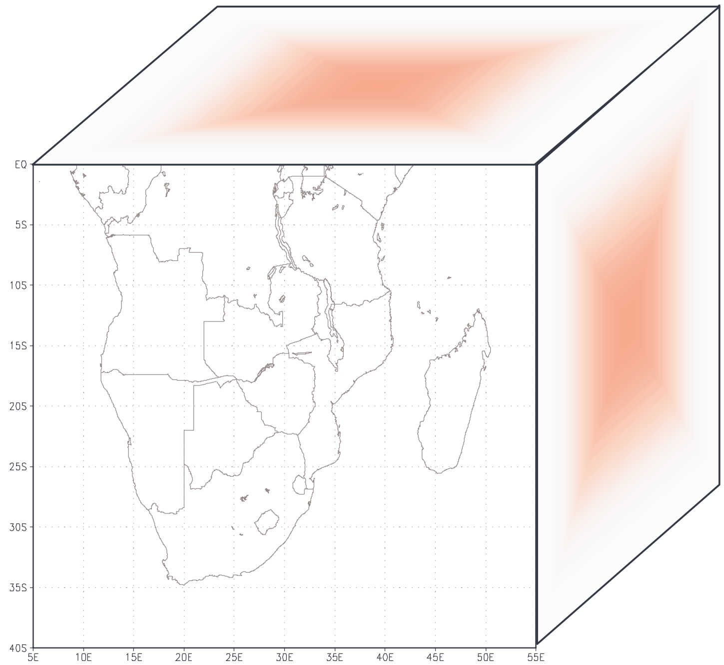
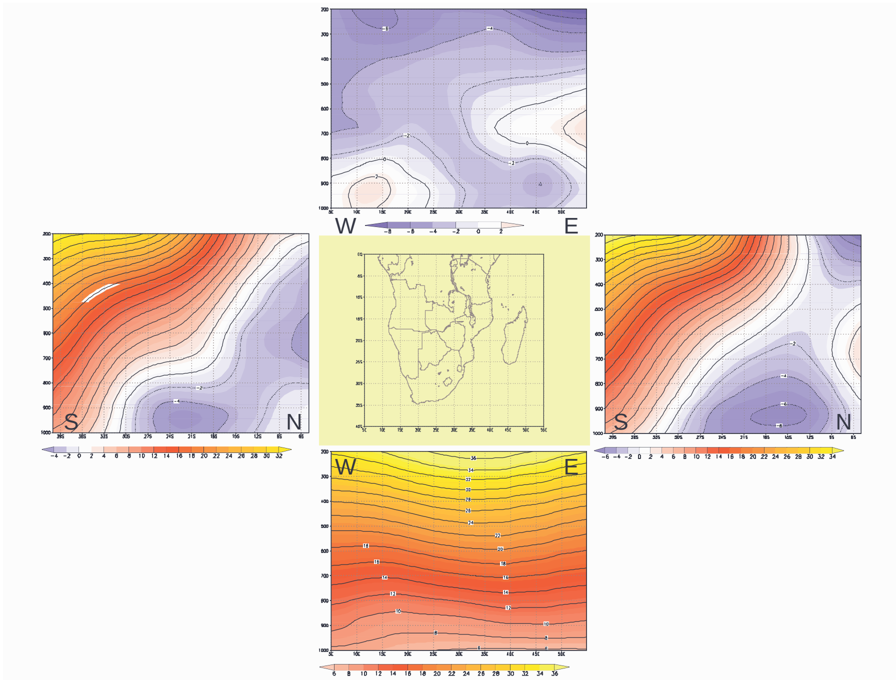


Figure 39: Graphical representation of the faces of the RCM domain for which the GCM data requires validation.



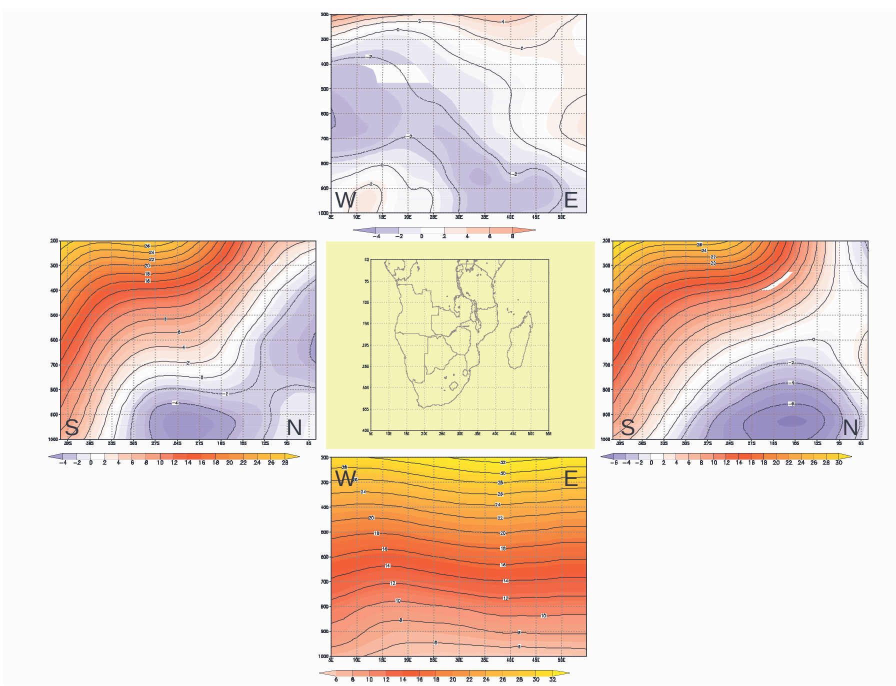


Figure 40: Mean u-wind component on the 4 domain boundaries. The top figure is for 20 years of data from the NCEP reanalysis ("observed"), and the lower figure from 30 years of the ECHAM GCM simulation of present day climate.

Figure 41 shows the range of states for the western face of the domain, using the 6-hourly data from the NCEP reanalysis and ECHAM simulations of the present day climate. Figure 42 shows the frequency of occurrence of these same states. From these figures it is immediately apparent that the ECHAM model has some bias; the ECHAM model has a tendency toward positioning the mid-latitude jet slightly north of the NCEP reanalysis data, and with a moderate decrease in intensity. However it is arguable that these differences are acceptable for the purposes of investigating climate change. The analysis shows the ECHAM GCM captures the dominant characteristics as seen in the NCEP reanalysis data, and the difference in intensity are accountable given that the NCEP reanalysis is constrained to match the point observations and will hence have higher variance and intensity.

Thus, in terms of the western face u-winds (a key variable in driving an RCM) for a domain over southern Africa, the ECHAM model would seem to provide a credible simulation of the climate, and hence be a valuable tool for assessing future climate change. Similar analyses can be undertaken for the other faces and variables, but are not presented here.

4.5 GCM skill resolution

One alternative to downscaling is to utilize the GCM simulation data directly. This does not provide adequately spatial resolution for many applications but may, nonetheless, provide insight into the broader regional changes. However, underlying this is the assumption that the GCM is skillful at the resolution used – necessitating some understanding of the “skill resolution”. Conventional understanding in the modelling community is that the skill resolution of any model is some aggregate of perhaps 7-9 grid cells. However, this is likely to be spatially dependant, and a more formal assessment is perhaps required.

One approach is to determine the convergence between the GCM and observed data (NCEP reanalysis fields) as a function of area aggregation. In this approach, for each grid cell, the following procedure is adopted: within an increasing radius around the grid cell, up to some defined maximum radius, the data are progressively aggregated in both the GCM and NCEP reanalysis data. When the GCM data has converged to within some defined range of the NCEP data (or the maximum search radius has been reached) the process is halted and the number of aggregated grid cells counted, and this value assigned to the grid from which the process began. The process is then repeated for the next grid cell. At the conclusion all grid cells have assigned a number representing the degree of spatial aggregation required to achieve convergence with observational data.

This approach has been applied to a number of GCMs to assess their skill resolution. Figure 43 shows the results for 4 GCMs, based on the skill resolution in simulating surface air temperature. From the figure it is immediately apparent that there is some degree of commonality between the GCMs; all appear to require more area aggregation (lower skill resolution) in regions of strong surface gradients of temperature, most notably in regions of strong topography. However, it is also clear that some models have unique problems in some areas. For example, with reference to the South African domain, the

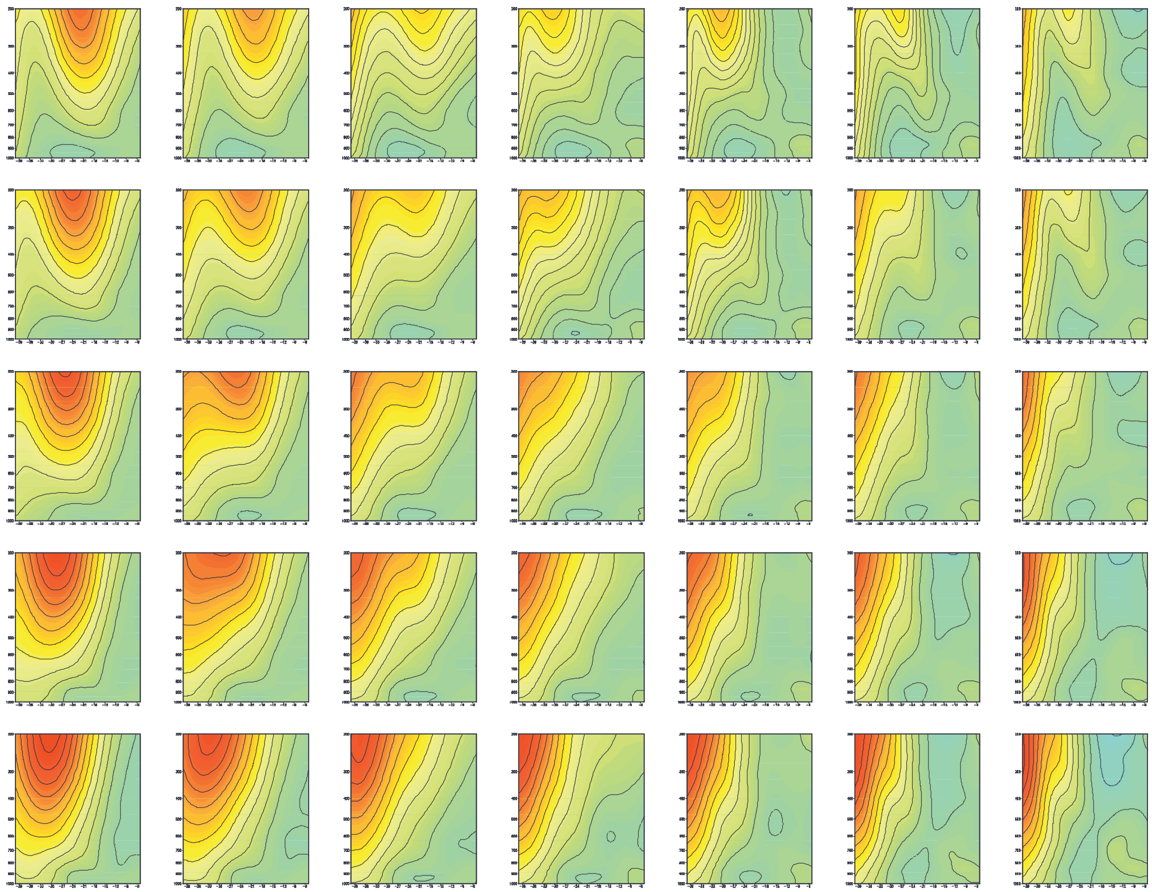


Figure 41: the array of possible states of u-wind on the western face of the RCM domain. The y-axis is the vertical dimension (in units of pressure), and the x axis spans the latitudes from south to north of the western face of the domain. Red indicates high positive values (westerly wind) and the blue indicates negative (dashed contours) easterly winds. The upper tropospheric mid-latitude jet stream is clearly seen.

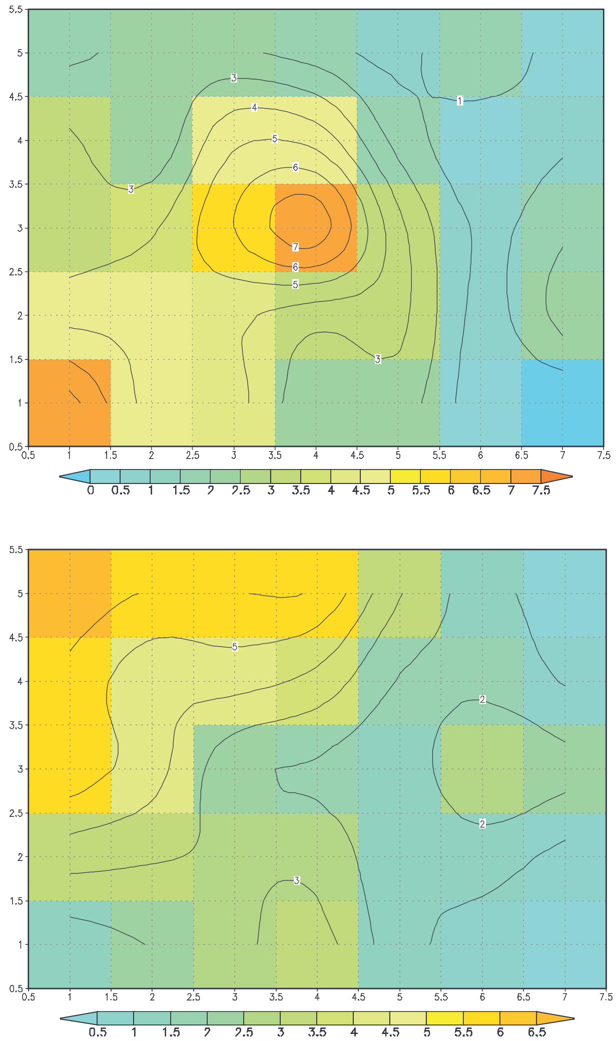


Figure 42: Frequency of occurrence (%) of each state as identified by the SOM in Figure 41. The top panel represents the frequency of occurrence in the NCEP reanalysis data. The lower panel shows the frequency of occurrence form the ECHAM GCM simulation of present day climate. The x and y axes refer to the archetypes in the array of Figure 41 (1,1 referring to the lower left corner of Figure 41).

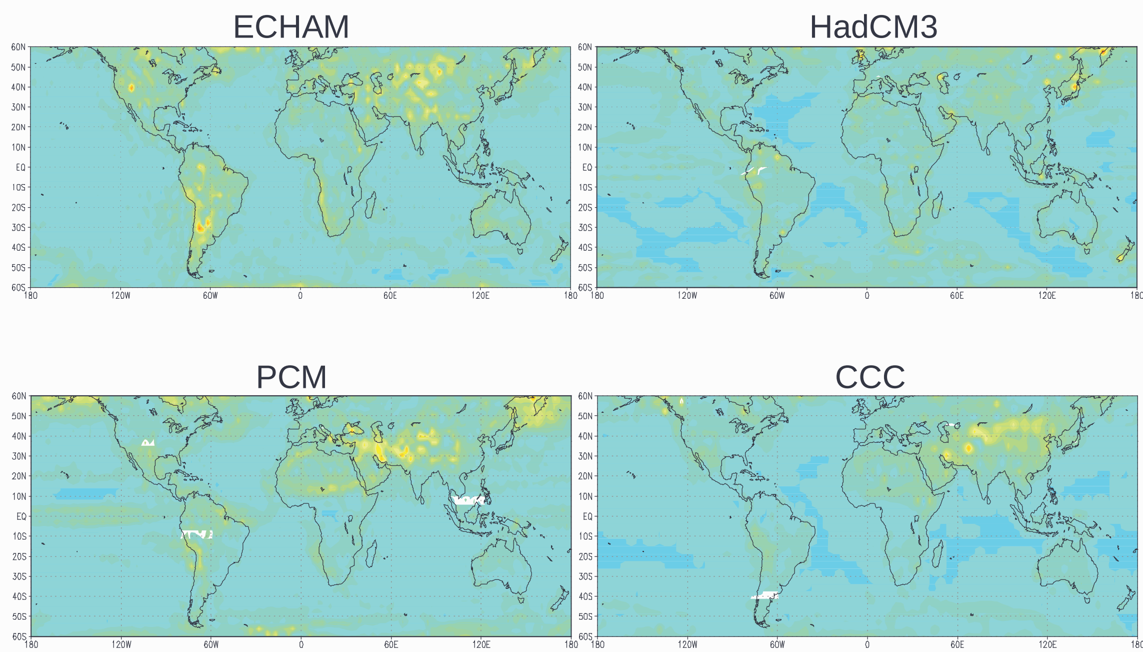


Figure 43: Relative skill resolution across four GCMs. Yellow to orange colours indicate regions where a higher degree of area aggregation is required to attain convergence between the GCM simulation of present day climate and the climate as represented by the NCEP reanalysis data.

HadCM3 model has lower skill resolution compared to the other models to the south of the continent, whereas the ECHAM model has lower skill resolution up the west coast.

Cognizance of these issues is important if further analysis of the potential impacts of climate change is to be undertaken on the basis of GCM simulations. This also serves to highlight the dangers in blindly using GCM data. Nonetheless there is much of value that may still be derived from GCMs, as discussed later in the section on GCM guided perturbations.

4.6 Climate change stationarity

Accepting that a given GCM may be valid for assessing climate change impacts in a region – at least in terms of the larger scale processes (synoptic scale) that are compatible with the GCM skill resolution – one may then consider the attributes of the projected climate change. Again it is important to recognize that change is an accumulation of changes on the weather event time scale. In the same way, changes may occur on the, for example, daily time frame that are not reflected in time-averages. Hence it is important to evaluate change in terms of daily synoptic (GCM skill resolution) events.

In this context change may be manifest in two forms: changes in the frequency, persistence, and recurrence of existing synoptic events, or change in the intensity and form of events beyond that which is experienced under the current climate. This latter issue is that of stationarity, and has serious implications for all forms of downscaling if it is shown that significant non-stationarity is projected for the future.

The SOM, as described earlier, is an effective tool for assessing both forms of change as outlined above. In this case the SOM is used to characterize the archetypical states of the synoptic circulation pertinent to a given region. In the example presented here the synoptic forcing in relation to the Western Cape is assessed. Figure 44 shows the SOM identification of characteristic circulation modes over the Western Cape as represented by a 15º domain (~1500km by 1500km) of the 850hPa geopotential height surfaces. The figure shows the typical state expected for the region; a range of high pressure systems typically associated with dry conditions, and low pressure systems reflecting weaker continental troughs, systems associated with tropical temperate troughs, and passing mid-latitude cyclones; the latter being the principal contributor for the winter rainfall of the region.

As with the SOM analysis presented earlier, the frequency of occurrence of these states may readily be determine; for both the GCM simulation of the present day climate and the future climate. Figure 45 shows the frequency of occurrence from 30 years of ECHAM simulation of present day climate, and the ECHAM simulation of the 2071-2100 period assuming growth in greenhouse gasses according to the SRES A2[9] scenario.

[9] The SRES scenarios are projections of greenhouse gas emissions into the future. The A2 scenario reflects a relatively high growth in emissions that would be associated with a "business as usual" approach by society.

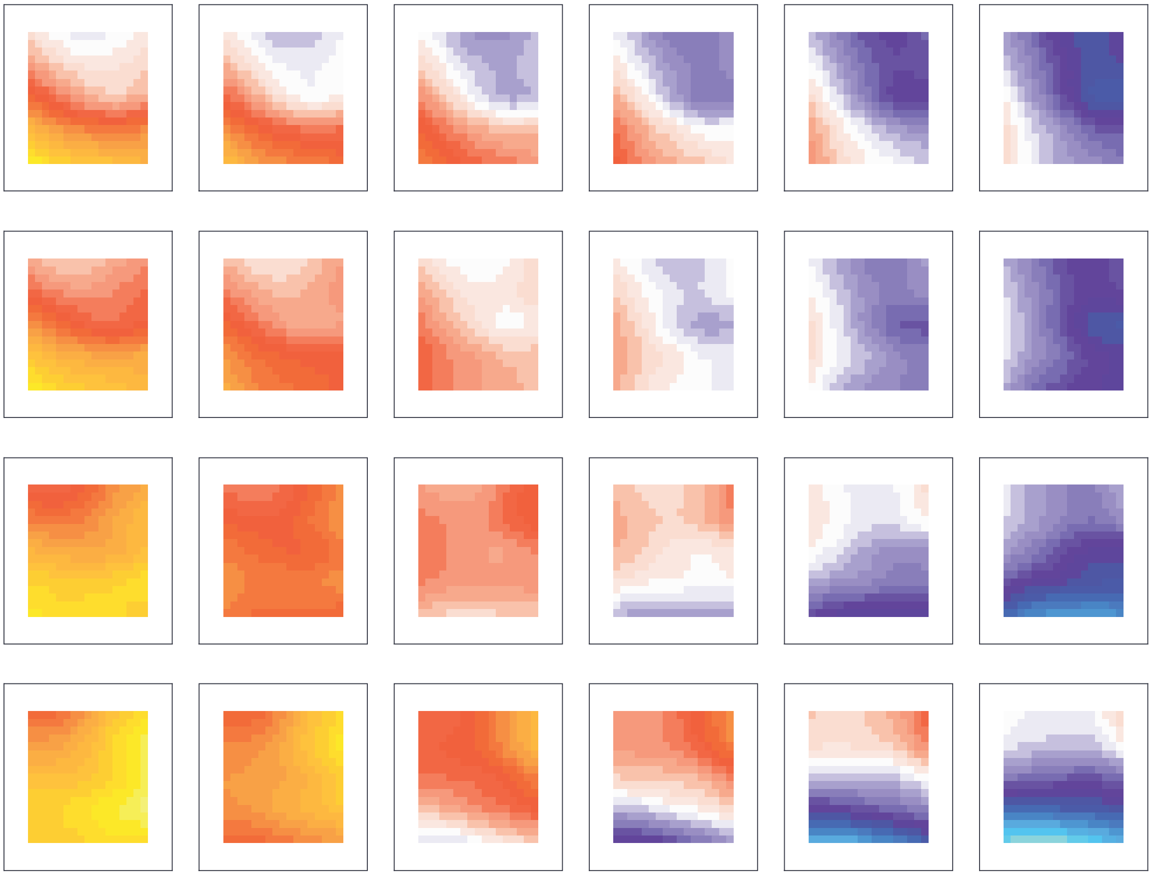


Figure 44: SOM-derived archetypes of 850hPa geopotential height fields for a 15º window centred on Cape Town, as simulated in 30 years of data by the ECHAM GCM. Red indicates high pressure, and blue is low pressure.

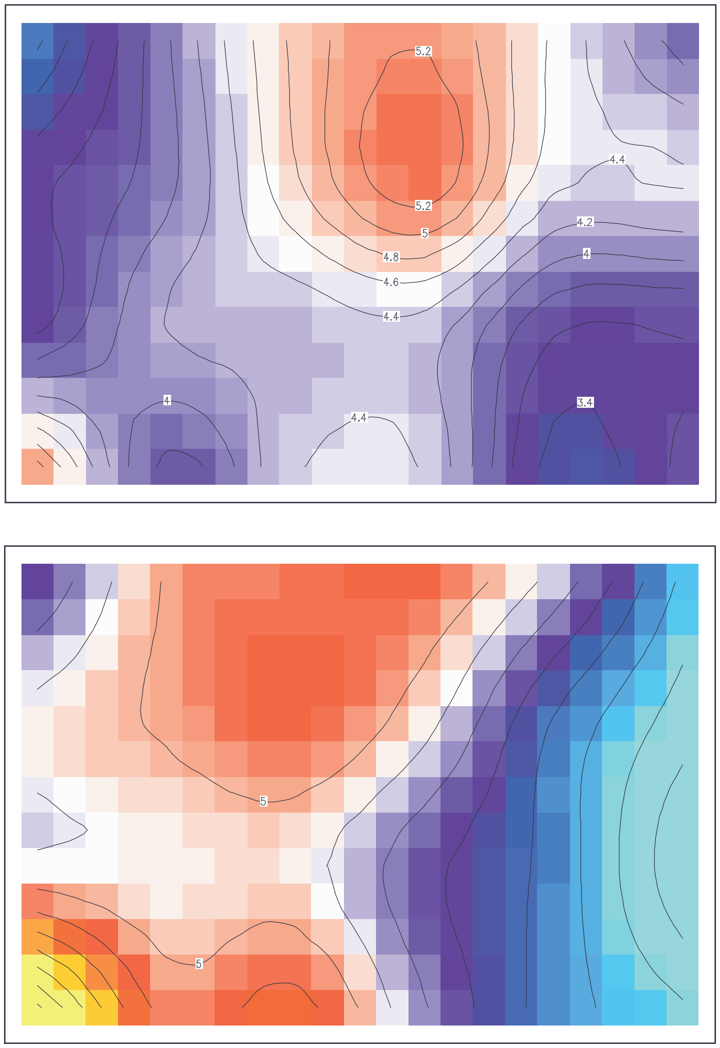


Figure 45: Relative frequency of occurrence of the archtypes of circulation in Figure 44. The top panel reflects the frequency of occurrence of archetypes under present climate conditions as simulated by the ECHAM GCM. The lower panel reflects the frequencies for the future climate of 2071-2100 as simulated by the ECHAM GCM forced with the SRES A2 greenhouse gas scenario.

The ECHAM simulation of the future climate shows clear and disturbing changes in the dominant circulation states. First is the strong increase toward an increased dominance by high pressure systems. This is coupled with a move of the occurrence of tropical temperate troughs and mid-latitude cyclones to those of less intensity. If this change of circulation were to be the only or dominant change, then the implications for water resources in the western Cape is not encouraging. If historical changes were to support this projected change, and if other GCM simulations were to concur, this would suggest there is credible basis for taking proactive adaptation to the implied reduction in water resources.

The SOM analysis may be further extended to consider the question of whether these shifts are possibly also indicative of a change in intensity and frequency of events that are rare in the current climate record. This is readily accomplished with the SOM by assessing what proportion of the future circulation events exceeds the intensity of current climate events. Formally, with the SOM this is accomplished by assessing the measure to which the archetype states match the simulated events – a measure of "goodness of fit". Calculating this one may calculate the frequency of future events that exceed the goodness of fit for current climate events, or that exceed the, for example, 90^{th} percentile value of the current events.

Figure 46 shows this measure for the same western Cape 15º domain. The total exceedance of future events is ~4.5%, or nominally 1 in 20 days. This exceedance is concentrated on the dominant high pressure systems, indicating that future high pressure systems over the Western Cape, as reflected in daily synoptic events, are likely to increase in intensity under future climate scenarios, at least as simulated by the ECHAM model.

4.7 Evaluation of GCM change – guided perturbations

This last section builds on the project discussion presented so far. In one sense the discussion that follows is not explicitly inherent in the project, yet is intricately related and of relevance to all sectors vulnerable to climate change, most notably the water sector. In the final analysis, when there are pressing needs for regional climate change information, and where appropriate downscaled information remains unavailable, end users can, with appropriate care, derive valuable information from the GCM simulations of future climate. Taking the above sections into account, many sectors of South Africa have yet to undertake even the most basic of sensitivity studies to assess vulnerability to climate change. The following suggestions are replicated from a recent article in the WRC publication "Waterwheel" (Hewitson, 2004).

- Assess the characteristics of relevance in the climate system for the water sector: which climate characteristics are important? For example, is it rainfall totals, interannual variability, seasonal timing, dry spell duration, extreme events, the histogram of daily rainfall magnitudes, return periods of rare events, etc?
- What multiplicative attributes may be important? For example: is temperature a complicating factor, is interannual variability important, does changing societal demand for a resource exacerbate potential climate change? Are there thresholds, which if exceeded by the climate system, will have an amplified consequence?

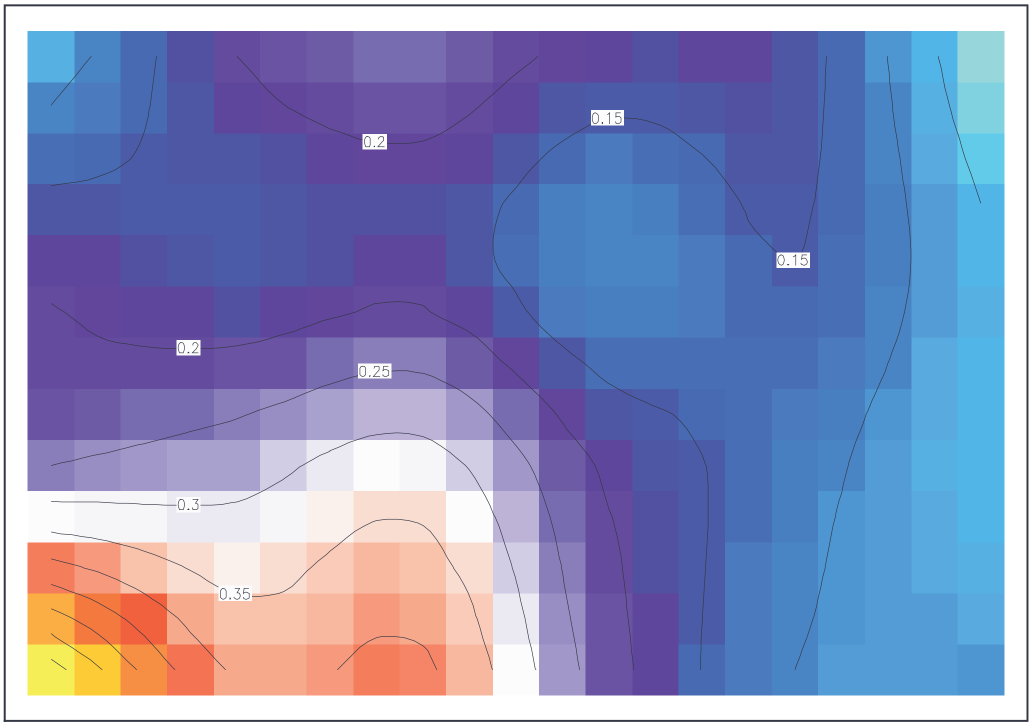
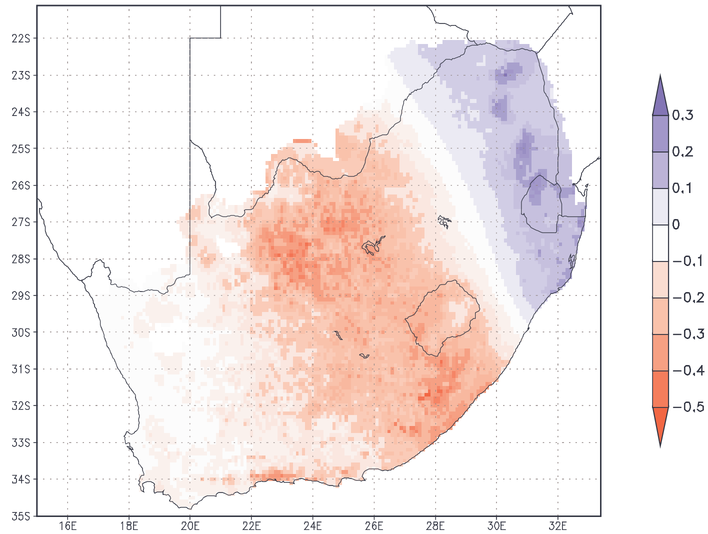


Figure 46: Percentage of events as represented by the archetype states centered on Cape Town shown in Figure 44, where the ECHAM GCM simulation of future climate events exceeds the intensity of present day events. Total % exceedance (summed across all SOM determined states) is approximately 4.5%.

- Undertake scenario based sensitivity assessments. For those variables identified above, explore what the consequences to the water sector would be for a perturbation of, say, a 20% decrease in summer rain with a 10% increase in dry spell duration and a 2ºC increase in minimum temperature.
- Examine the past record for evidence of changes in these attributes – change detection. This requires careful quality controlled data, assessing the spatial representivity of the data, and understanding the limitations and possible misleading characteristics of the chosen analysis method.
- Consider the projections of future change. There are a number of approaches to this, from the simple to more sophisticated downscaling and probabilistic approaches.
- Consider adaptation possibilities. Are there strategies that can be adopted that would minimize the impact of climate change? Are there "no-regrets" policies that could be implemented that are beneficial regardless of the climate change?

The above may be seen as guidelines for "good practice" in any sector assessing the climate change implications. Each of the suggested steps is readily undertaken by the relevant experts in each sector, with perhaps the exception of accessing the projections of future change. In this regard the sophisticated approaches, be they RCM based or empirical downscaling, require care in development and application. However, the basic GCM data may be robustly used to guide the development of sensible perturbations for assessing sensitivity to climate change. Hewitson (2003) outlines a simple approach as follows: Spatially smooth the GCM data in recognition that the raw grid cell data are not the skill scale. Spatial smoothing, in effect a spatial aggregation for each grid cell, filters the data to emphasize the skilful scale of the GCM. This smoothed GCM field of the future climate may then be difference from the smoothed fields of the simulation of the present climate. The differences may then be applied to observational data as a perturbation that is consistent with the GCM skill-scale projection of future climate changes.

Figure 47 present the change in precipitation as simulated by two GCMs where the GCM fields have been smoothed and the climate change diference applied to a 10km gridded precipitation data set (Hewiston, 2004). Of note in this approach is that the projected change by the two GCMs has a notable degree of agreement



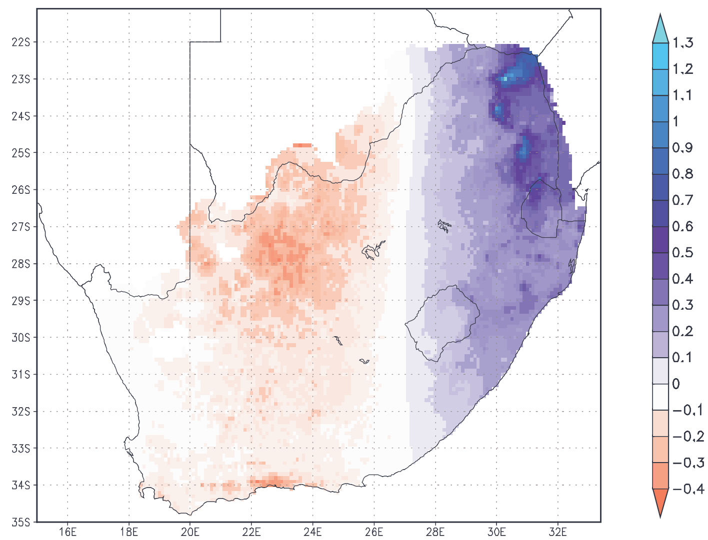


Figure 47: Precipitation anomaly (mm/day) of a gridded DJF baseline climatology using the GCM percentage change. This represents a guided perturbation of the current observed climate, guided by the spatial large-scale anomaly from the HadCM3 (top) and the ECHAM4 (lower) models simulation of the future climate.

5. Summary and conclusions

This project, which began with broad ambitious objectives, has made significant strides in developing model-based approaches to key research questions of the southern Africa climate system. In particular the project has elucidated new avenues of concern for further research, and complemented other activities, which, in the absence of this WRC project, would not have been able to make the progress that has been achieved.

The capacity developed in terms of infrastructure and scientific personnel has been substantially advanced, and as a direct consequence there are active research lines being followed by post-graduate students and other established researchers who now utilize climate models as the principal tool. Collaboration between institutions both nationally and internationally has been enhanced, with stable research relationships developed with some of the leading international researchers.

Notable in terms of sustainability, a number of proposals are currently awaiting decision or in preparation (including to the WRC) which are headed by researchers who have developed many of their skills as a direct consequence of this project.

For many years excellent ground-breaking research has focused on the role of the oceans in governing the climate variability of southern Africa. Yet it remains that under weak teleconnection forcing there are significant unknowns regarding the governing processes that lead to the high degree of inter-annual variability. The modelling work undertaken in this project has investigated the complexity of the climate system of southern Africa, elucidating key sensitivities surrounding feedback mechanisms and dynamic responses to external forcing that are only now beginning to be understood in terms of their relevance to many sectors of society activities.

Importantly, especially in the light of the vulnerability to the climate system and in the face of accelerating climate change, the project has demonstrated the importance of land-surface feedbacks to the atmosphere. These feedbacks are important given the ongoing land use change, the strength of the atmospheric response to these feedbacks which is commensurate with the magnitude of inter-annual variability and projected climate change, and that the feedbacks are possibly positive – potentially exacerbating any climate change signal. The suggestion arising from these results is that the land-surface may play a notably more important role than perhaps previously anticipated in governing intra-seasonal variability, extreme events, and possibly the strength of the regional climate response to global climate change.

On the side of capacity, the project has refined the modelling tools, and in the process identified key attributes of importance for modelling the regional climate system. These developments coupled with the experiential skill developed by the modelling team would suggest that the tools may now be robustly applied to further our understanding of the key dynamics of the climate system, especially in regard to the question of climate change.

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Appendix 1: Summary of technology transfer and capacity building

Technology transfer:

This work has received direct support from a number of complementary projects. These include the AIACC project on climate change in Africa, the Dept. Arts, Culture, Science and Technology funded project on seasonal forecasting, and the current WRC project K5/1430 on impacts of climate change on water resources with the Universities of Pretoria, Witwatersrand, KwaZulu-Natal and Cape Town.

Physical Capacity:

The infrastructure developed through this project has been co-funded with other projects funded by the NRF, other WRC projects, and the DACST Innovation Fund project on seasonal forecasting, together sustaining a computational infrastructure capable of handling the research tasks, and also supporting other climate related research. At present the infrastructure consists of (collectively from all funding sources):

- PC cluster computer systems
- Shared memory multiprocessor computational servers
- Data storage to 9 TerraBytes

In addition are tape storage services and older computer systems no longer meeting the computational demands.

Human capacity (participants/contributors to project):

Name	*Institution*
Hewitson, B	UCT
Reason, C	UCT
Tadross, M	UCT
Main, J	UCT
Jack, C	UCT, PhD
Walawege, R	UCT, PhD
Drew, G	UCT, PhD
Barrable, A	UCT, PhD
MacKellar, N	UCT, MSc
Hansingo, K	UCT, MSc
Mdoka, M	UCT, MSc
Guy Midgely	National Botanical Institute
Tennant, W	SA Weather Service, PhD
Landman, W	SA Weather Service
Gutowski, W	Iowa State University

Peer reviewed publications drawing directly on this project

Hewitson, B.C. and Crane, R. 2003. Gridded area average precipitation via conditional interpolation. In press in *Journal of Climate*

Cook, C., Reason, C.R., Hewitson, B.C. 2004. Wet and dry spells within particularly wet and dry summers in the South African summer rainfall season, *in press* in Climate Research.

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Appendix 2: Data archiving and access.

All data sets used and generated in this work are archived on the CSAG computer system at UCT. The data sets are in binary format and require appropriate software (free) for visualization. Further, the data sets are large, in some cases in excess of 2 Gbytes per file, and are thus only accessible through a logon on the CSAG system, or distributed on DVD discs on request.